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Performance Evaluation of Data Dissemination Protocols for an Infrastructure-to-Vehicle Cooperative Traffic Light Application

Master Thesis Telematics

Chair for Design and Analysis of Communication Systems (DACS)
Faculty of Electrical Engineering, Mathematics and Computer Science
University of Twente, The Netherlands

Author:
Dennis Sluijsmans
Student nr.: s0027111

Supervisors:
Wouter Klein Wolterink, MSc. (UT)
Dr. ir. Geert Heijenk (UT)
Dr. ir. Georgios Karagiannis (UT)
Robbin Blokpoel, MSc. (PEEK Traffic)

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Abstract

Cooperative systems based on Infrastructure-to-Vehicle (I2V) wireless communication offer promising opportunities for automotive safety and traffic efficiency improvements. This research proposes a cooperative traffic-light system based on wireless I2V communication between vehicles and fixed Road Side Units (RSUs) deployed at intersections. This application, called the Cooperative Traffic Light Assistant (CTLA), is directly connected to a Traffic Light Controller (TLC) and therefore able to disseminate TLC related data. Approaching vehicles receiving this data can react in different ways, e.g. by adjusting their speed or by choosing an alternative route. The objectives of using such kind of traffic efficiency applications ranges from minimizing the average travel delay of approaching vehicles to reducing overall fuel consumption and pollutant emission.

This research includes the design of three dissemination protocols for the CTLA application. These dissemination protocols can be differentiated by their application trigger condition, the reception pattern, and the routing technology. In addition, multi-hop Vehicle-2-Vehicle (V2V) communication was added to increase the coverage area.

All three dissemination protocols have been implemented in the VANET simulator iTETRIS to perform several large scale experiments. The results of the experiments showed that all three dissemination protocols where able to handle the addition of vehicles in large scale scenarios without suffering noticeable loss in performance.

Samenvatting

Coperatieve systemen op basis van Infrastructuur-to-Vehicle (I2V) draadloze communicatie bieden veelbelovende mogelijkheden voor de veiligheid van weggebruikers en en optimalisatie in het verkeer. Dit onderzoek introduceert een coperatieve verkeerslicht systeem op basis van draadloze I2V communicatie tussen voertuigen en vaste Road Side Units (RSUs) ingezet op kruispunten. Deze applicatie, genaamd de Cooperatieve Traffic Light Assistant (CTLA), is rechtstreeks aangesloten op een Traffic Light Controller (TLC) en daardoor in staat om TLC gerelateerde gegevens te verspreiden. Naderende voertuigen die deze gegevens ontvangen kunnen op verschillende manieren reageren, bijvoorbeeld door het aanpassen van hun snelheid, of door te kiezen voor een alternatieve route. De doelstellingen voor het gebruik van dergelijke verkeers efficiency toepassingen variren van het minimaliseren van de gemiddelde reis-tijd tot vermindering van de totale brandstofverbruik en uitstoot van vervuilende stoffen. Dit onderzoek omvat het ontwerp van drie protocollen voor de verspreiding van de CTLA data. Deze protocollen onderscheiden zich van elkaar op het gebied van de applicatie-trigger conditie, het uitwisselingen patroon en de routing technologie. Daarnaast wordt multi-hop Vehicle-2-Vehicle (V2V) communicatie toegevoegd om het bereik van de applicatie te vergroten. Al deze drie protocollen zijn gemplementeerd in de VANET simulator iTETRIS om zo verschillende grootschalige experimenten uit te voeren. De resultaten van de experimenten toonden aan dat alle drie de protocollen in staat waren om met de toevoeging van voertuigen in grootschalige scenario's om te gaan, zonder dat de prestaties van de applicatie daar onder leden.

Contents

Chapter 1

Introduction

With the introduction of vehicles and road infrastructures in the early days new problems arised such as efficient traffic regulation and traffic congestion. After a while governments started to introduce traffic management systems which finally evolved into advanced traffic systems currently known as Intelligent Transportation Systems (ITS). The IEEE Intelligent Transportation System Society [22] describes ITS as "those utilizing synergistic technologies and systems engineering concepts to develop and improve transportation systems of all kinds". Traditional ITSs vary in technologies applied, from basic management systems such as car navigation, traffic signal control systems, variable message signs, automatic number plate recognition or speed cameras to monitor applications, such as security camera systems. However, with the latest developments in communication technology, ITS is pushed into a whole new area of research.

As communication technology continues to become more and more affordable, an increasing number of everyday objects participate in today's interconnected world. Today, most of us already live in an "on-line" world where we can communicate immediately and basically with anyone, or any organization anywhere in the world. With the increasing popularity of communication technology implemented in mobile devices, the number of developments in technology that operate in a peer-to-peer manner (i.e., Mobile Ad-hoc NETworks or MANETs) is still growing. In the future, the interaction of physical objects is envisioned to facilitate new services that improve our everyday lives. One aspect of this ubiquitous connectivity [28] is *inter-vehicle communication*, aiming at increasing comfort and safety of the driving experience as well as at reducing fuel consumption and emissions to mitigate the environmental impact. With the start of inter-vehicle communication research in the mid nineties, the term Vehicular Ad-hoc NETwork (VANET) showed up, which could be considered as an instantiation of a MANET. Cooperative ITS is the major application of VANETs. With the introduction of VANETs, developments in the area of ITS where taken into a whole new level.

Over the last years a large number of research groups, automotive manufactures, institutions and standardization bodies have been working worldwide in the field of cooperative ITS. Starting with the idea of making driving safer by inter-vehicle communication, the concept of VANET has been extended to a large collecti on of applications that can profit from wireless communication between vehicles. These developments resulted in a wide range of protocol stacks suitable for the vehicle environment. Among the different candidates for the standard wireless technique for ITS communication, the recently standardized WLAN amendment IEEE 802.11p [50] (and its European variant ITS-G5 [43]) is gaining high popularity.
By now, vehicles are not only envisioned to communicate between each other, but also to get information from and send data to infrastructural units. These stationary parts of the vehicular network range from traffic lights and dynamic traffic signs to access points at home, gas stations, and elsewhere. In addition, although active safety applications still represent the central idea, traffic efficiency applications as well as entertainment and business applications have also been proposed [76].

1.1 Motivation

In large and especially distributed systems or networks, scalability is a very crucial characteristic. Scalability - in the context of VANETs - is defined as the ability to handle the addition of vehicles without suffering noticeable loss in performance or increase in administrative complexity [61]. In the VANET scenario, scalability issues arise in several different contexts. The number of transmitting vehicles has an impact on network connectivity and on the likelihood of congestion on the wireless channel. In addition, protocol design has a great impact on scalability.
As vehicular communications research becomes popular, there is also an increasing interest in addressing the scalability issue [37, 55, 36, 61]. However, these studies address the scalability of safety applications, not of traffic efficiency applications.

This research focuses on the performance on an Infrastructure-to-Vehicle (I2V) - traffic light related - traffic efficiency application. I2V applications run on both the infrastructure Road Site Units (RSUs) and the vehicle's On Board Units (OBUs). The traffic light application used in this research is directly connected to a Traffic Light Controller (TLC) and therefore able to disseminate TLC related data. Approaching vehicles receiving this data can react in different ways, e.g. by adjusting their speed or even by choosing an alternative route. The objectives of using such kind of traffic efficiency applications ranges from minimizing the average travel delay of approaching vehicles to reducing overall fuel consumption and pollutant emission.
Although several projects addressed this kind of traffic efficiency application (or an analog version) the main focus of these studies - and of most studies on I2V traffic efficiency applications in general - is (1) on building a proof of concept [35, 17, 7] or (2) evaluating the application's performance by means of indicating the reduction of the overall fuel consumption [11, 77, 47]. Performance of the underlying network is assumed as optimal or based on assumptions, and - to the best of our knowledge - scalability is not addressed at all.

1.2 Objectives and scope

In this research we evaluate the performance of several dissemination protocols for an I2V traffic efficiency application. Based on the results of related studies and our assumptions, we specify a list of requirements for our proposed Cooperative Traffic Light Assistant (CTLA) application. In order to find a suitable solution, we address the following questions:

- What are the requirements of the Cooperative Traffic Light Assistant (CTLA) application?
- Which data should be exchanged between vehicles and Road Side Units (RSUs) and what are the exchange patterns?
- To what extend is the Cooperative Traffic Light Assistant (CTLA) system scalable?
- Which dissemination protocol can be advised as the optimal protocol for the Cooperative Traffic Light Assistant (CTLA) application?

Based on these research questions, we define the main objectives as: (1) identification of the data exchange patterns for the CTLA application and (2) provide insight in the performance of the I2V communication.

We constrain our research on wireless communication to one communication technology; mainly because of IEEE 802.11p/ITS-G5's popularity we decided to choose this technology as the underlying communication technology.
It should be emphasized that the contribution of this research is the investigation of wireless communication for an I2V traffic efficiency application, and not on creating the optimal traffic light I2V application. However, the results of this research may be useful to further studies on traffic-light I2V applications that uses IEEE 802.11p/ITS-G5 as the underlying communication technology.

Furthermore, the focus is not on newly optimizing traffic-light approaching behaviour. The art of realistic modelling how drivers approach a traffic light controlled intersection falls in the area of traffic engineering, therefore we will make some assumptions about driving behaviour and argue the impact of it on the results.

1.3 Methodology

This research uses three methodologies: literature study, system design and simulation. This background knowledge enables us to specify our proposed CTLA application. Specifications that can not be formulated based on standards and related work will be provided as assumptions. After specifying the CTLA application, we design three dissemination protocols which can exchange application data between a vehicle and a RSU.
The results are obtained by means of simulation experiments. Though a real-life deployment scenario is more realistic than simulation, such a scenario requires hundreds or maybe thousands of equipped vehicles which seems to be an inefficient method in order to get large scale results. A simulation seems at first sight a good alternative but a certain level of realism must be guaranteed in order to get representative results. The results should provide us the necessary insights to determine what is the optimal dissemination protocol for the CTLA application.

1.4 Outline

The outline of this research is as follows. Chapter 2 provides the literature study, which starts with the background information of the standardized wireless technologies for cooperative ITS. Also, this chapter includes a brief description of dissemination techniques commonly used in the VANETs.
Chapter 3 includes the specification of our proposed CTLA application. This chapter describes the use case, the CTLA application, the requirements and the assumptions.
Chapter 4 describes the design of three dissemination protocols for the CTLA application. The background information for the network technologies used by these three dissemination protocols can be found in the first chapter. Chapter 5 provides an performance analyses of the CTLA dissemination protocols. In order to get quantitative results, an existing VANET simulator has been modified to meet the CTLA specifications. This chapter describes the simulation experiments and their outcomes.
Finally, in chapter 6, we provide an analysis and conclusion of our findings. We end this chapter with recommendations and some comments on further work.

Chapter 2

Background

In the first section we introduced the Cooperative Traffic Light Assistant (CTLA), a cooperative traffic efficiency application which uses a Vehicular Ad-hoc NETwork (VANET) with its ad-hoc WLAN technology as the underlying communication network. The subsequent sections describes the CTLA application and its large scale performance into more detail.
This section provides the necessary background information in the field of ITS, VANET communication and VANET simulation. By first describing WLAN, and in particular the amendment for the vehicular environment IEEE 802.11p, we provide the basic insights needed to understand the performance evaluation of section 5. The performance of the CTLA application will be evaluated by means of a VANET simulator. As will be explained in section 2.4 VANET simulation includes a combination of mobility modelling and wireless communication modelling. The concepts of VANET simulation and the integrated simulator used in our research are briefly explained in this section. We end this section with a description of radio wave propagation modelling.

2.1 Intelligent Transportation Systems

The IEEE Intelligent Transportation System (ITS) Society describes ITS as 'those utilizing synergistic technologies and systems engineering concepts to develop and improve transportation systems of all kinds' [22]. Clearly, the field of ITS is not restricted to vehicles, but involves the development of advanced traffic systems for all kind of transportations. Traditional ITSs vary in technologies applied, from basic management systems such as car navigation, traffic signal control systems, variable message signs, automatic number plate recognition or speed cameras to monitor applications, such as security CCTV systems.
First we illustrate the European standardization process. Then, we briefly describe the architecture components and the proposed architectures so far.

2.1.1 ITS standardization

The vast work on applications and technologies, protocols, and security mechanisms in current European research shall fit into one overall architectural framework moderated by the European project Communications for eSafety (COMeSafety). COMeSafety supports the eSafety Forum issues related to V2V and V2I communications as the basis for cooperative intelligent road transport systems. It provides an open integrating platform, aiming for the interest of all public and private stakeholders to be represented [32]. The results from major R&D projects such as CVIS [6], SAFESPOT [17], COOPERS [5], GeoNet [8], PReVENT [16], NoW [12] and SeVeCom [18] have been consolidated by a group of experts (called the Architecture Task Force), and submitted to European and worldwide standardisation bodies. In order

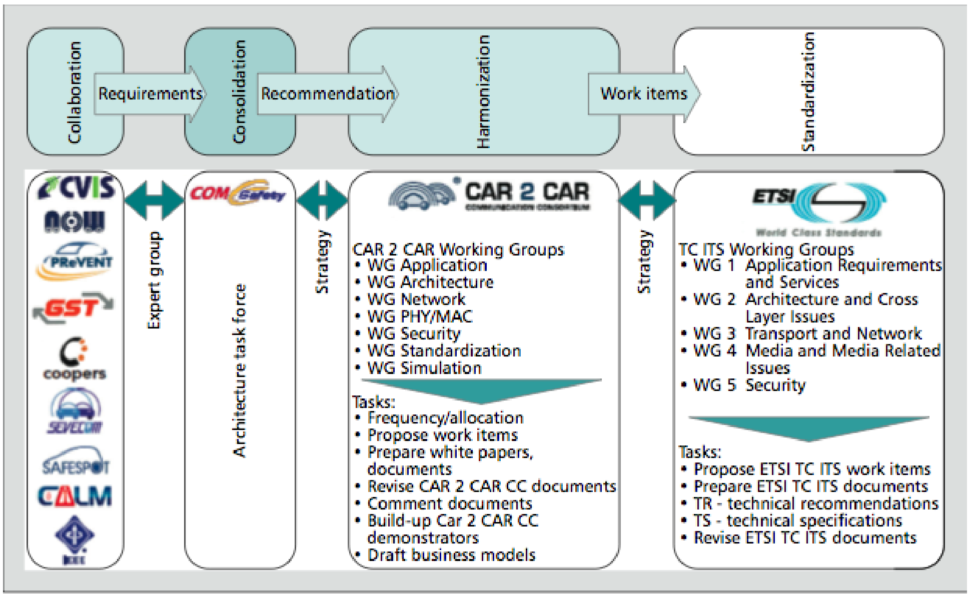


Figure 2.1: European standardization process of cooperative its systems (copied from [62])

to achieve wide acceptance and prepare European standardization at the European Telecommunications Standards Institute (ETSI) [2], the Architecture Task Force worked in close cooperation with the Car2Car Communication Consortium (C2C-CC) [1] and relevant standardization bodies such as the Internet Engineering Task Force (IETF) [3] and the International Standards Organization (ISO) [84]. In essence, results from European research projects have provided the basis for consolidation. Recommendations were derived for further consideration in C2C-CC. Out of the consortium, work items are proposed for standardization at ETSI. The whole process up to standardization is depicted in figure 2.1. An important result of the efforts of the COMeSafety project is the technical report *European ITS Communication Architecture*, initially released in 2008 and finally released as the third version by 2010. The standardization bodies, which will be discussed in the next section, used this report as a recommendation to standardize the ITS architecture.

2.1.2 ITS communication architecture

Vehicles communicate with each other via Vehicle-to-Vehicle communication (V2V) as well via Vehicle-to-Infrastructure (V2I) communication, or the other way around (I2V). Both types of communication are often referred to as V2X or C2X communication. Other commonly used terms are Inter-Vehicle Communication (IVC) or Car-to-Car (C2C) communication which refer to V2V communication, and Roadside-to-Vehicle Communication (RVC) or Car-to-Infrastructure (C2I) communication which refer to V2I communication, as will be described in section 2.2.
While different projects active in the field of ITS research started to disclose their developed V2X communication systems, standardization organisations started to standardize the results to a common V2X communication architecture. As a result, at the time of writing there exists a range of standardized V2X communication architectures proposed by organisation such as ISO, ETSI, and Institute of Electrical and Electronic Engineers (IEEE). In order to understand the elements used in these communication architectures, we start with an illustration of the concepts of ITS communication as described in the European ITS communication architecture. Then, we will describe the three main V2X communication architectures: IEEE WAVE, ISO CALM and the ETSI reference architecture.

Architecture components

The European ITS communication architecture described in the deliverable [32] is a communication system designed to connect ITS stations. Several types of ITS stations exist: central station, personal station, vehicle station and road-side station. Each of the four stations usually contains a gateway to connect the station to legacy systems. Figure 2.2 illustrates the station types and their architectures.
Depending on the deployment scenario, the four station types can be composed arbitrarily to form a cooperative ITS. Several communication networks are available to establish a connection between the ITS stations, e.g. Dedicated Short Range Communications (DSRC) [75], ITS-G5 [43], Cellular, Satellite. The communication could be performed directly between two subsystem component instances, or indirectly via intermediate sub system component instances. Hence, ITS stations basically provide communication capabilities and an application run-time environment.

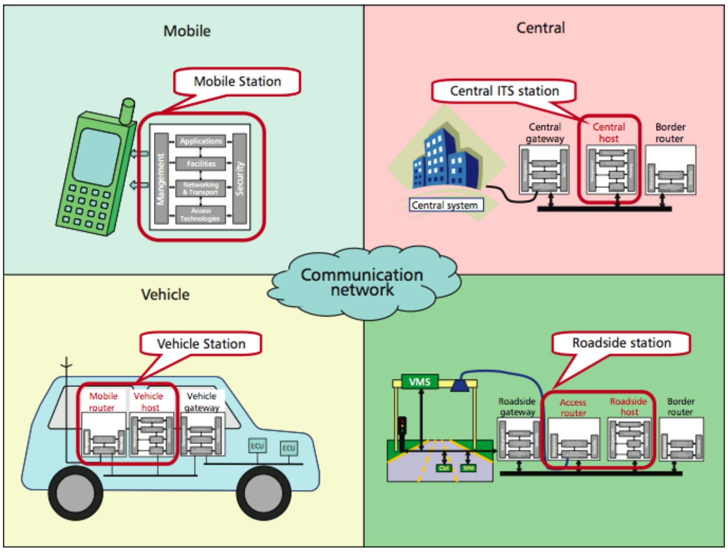
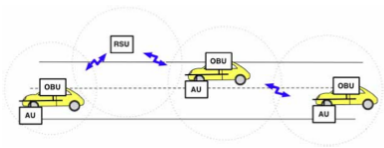


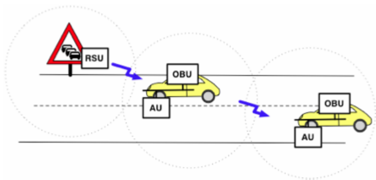
Figure 2.2: ITS communication architecture (copied from [32])

Each station can be equipped with multiple network devices, e.g. to provide ad-hoc communication or internet access. The architecture described by COMeSafety does not bind all ITS functionality to one node, on the contrary functions can be split into several physically separated nodes communicating over a Local Area Network (LAN). The entity responsible for facilitating an application run-time environment is often denoted as Application Unit (AU) [31, 35]. The decision of how to implement the required set of functions of an ITS station is left to the stakeholders to deploy this ITS communication architecture.
The communication of a vehicle station is the responsibility of the On-Board Unit (OBU). The OBU includes one or more network devices and on top the routing functionality. It also provides services (by means of service access points) to the AU. OBU functions and procedures include wireless radio access, infrastructure-based and ad-hoc routing, network congestion control, reliable message transfer, data security, IP mobility support, and others. We will discuss several of these concept throughout this section.
A road-side station contains a Road-Side Unit (RSU): this is either a physical device located at fixed positions along roads and highways, or a device at dedicated locations such as gas station, parking places, and restaurants. The communication scenario of a RSU depends on their current mode which can be one of the following: communication range extending, acting as an information source (e.g., by running a traffic efficiency application), or providing a internet access by acting as a relay. Figure 2.3 illustrates the three communication scenarios of a RSU.

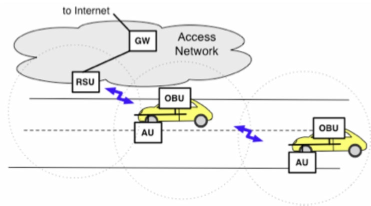
Several standardization organisations proposed a communication protocol stack: the IEEE organization standardized a complete V2X protocol stack following the ISO/OSI reference model (ISO Reference Model for Open Systems Interconnection), the ISO standardization organisation standardized an architecture with the objective to easily adapt new communication technologies, and the European standard-



(a) communication range extending



(b) information source



(c) internet relay

Figure 2.3: RSU communication scenarios (copied from [31])

ization organisation specified a standard based on the efforts of IEEE and ISO. The following sections will describe these standardization efforts into more detail.

IEEE WAVE

The IEEE organization standardized a dual protocol stack of the 1609 protocol family and the IEEE 802.11p technology, commonly known as Wireless Access in Vehicular Environment (WAVE). In terms of the OSI model [88], the IEEE 1609 framework builds on IEEE 802.11p as PHY/MAC and provides two parallel stacks on top of it; one for UDP/TCP over IPv6 and a proprietary one called Wave Short Message Protocol (WSMP). The reason for having two protocol stacks is to accommodate high-priority, time-sensitive communications, as well as more traditional and less demanding exchanges, such as UDP/TCP transactions [79]. Most safety applications require very strict requirements on latency and error probability [87]. WSMP enables the application to send short messages and directly control certain parameters of the radio resource, like data rate and transmit power level, to maximize the probability that all the involved parties will receive the messages in time.
The WAVE standards do not specify session, presentation, or application layers. However, they do introduce two elements that do not fit easily within the boundaries of the OSI model: the resource manager and the security services blocks [79]. Figure 2.4 shows the protocol stack of IEEE WAVE.

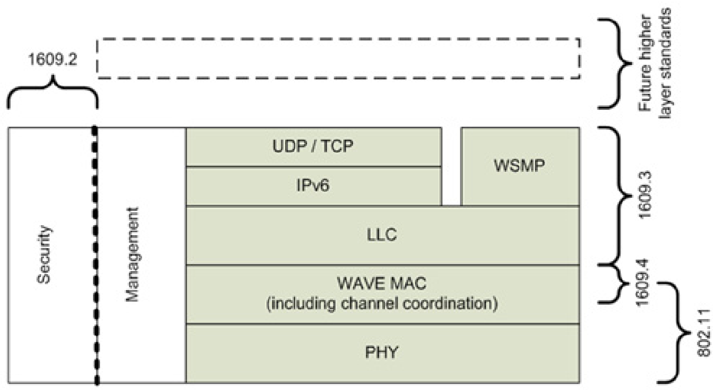


Figure 2.4: IEEE WAVE protocol stack (copied from [79]

Many researchers have investigated the various aspects of WAVE. In particular, research has been performed on the protocols of the two IEEE 802.11p layers. In section 2.3.2 we will discuss the IEEE 802.11p standard and its European variant ITS-G5 will be discussed in more detail.

ISO CALM

Communications Access for Land Mobiles (CALM) is a family of standards for continuous communications access for land mobiles standardized by the ISO TC 204/Working Group 16. The main rational behind CALM is to provide an uniform framework for communication access, which is independent of the communication access technologies. The CALM standard solves the problem of continuously building and deploying new access technologies, thus extending the lifetime of equipment installed in vehicles and infrastructure.
CALM applications and communication access technologies can be added and removed without affecting each other, which offers great flexibility in implementation. Furthermore, the CALM framework is capable of providing a continuous connection to the applications if at least one of the communication technologies is available. The available communication technologies offered to the applications can be mapped automatically by the framework intelligence, providing an optimal communication route, or configured by the applications. For example, the communication interface CALM M5 [84] is compliant with the IEEE 802.11p standard.
The CALM building blocks can be illustrated in the context of the OSI model as shown in figure 2.5. All the four building blocks of the communications kernel shall be addressed within a CALM compliant system, eventually distributed over several physical devices. The highest layer offers a standardized Application Programming Interface (API) towards user applications and comprise the OSI session, presentation and application layer.

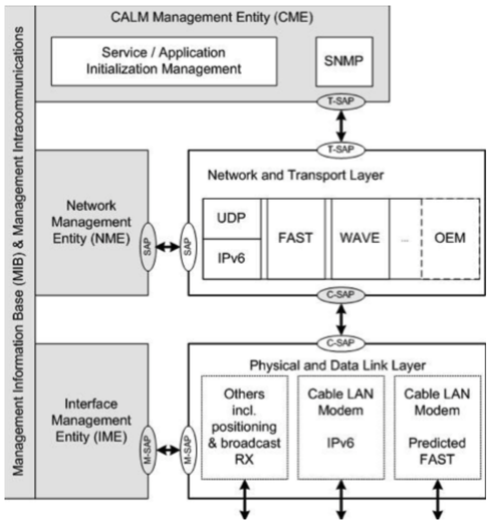


Figure 2.5: ISO CALM basic architecture copied from ([83])

Besides the common TCP/UDP layer in combination with the IP layer, CALM includes an additional network and transport layer for the support of applications with severe timing constraints and low latency requirements. This kind of applications can use the CALM FAST protocol specified in [85] for unicast and broadcast on a single hop basis. The CALM FAST protocol includes a service advertisement mechanism to inform other vehicles about their services. The service initialization phase exchanges address and application information. The Service Advertisement Frame (SAF) is sent on request of the group cast manager in the router of the provider and subsequently broadcasted by the MAC layer. A SAF includes a list of services offered by the provider, in addition to a list of available channels. The update frequency of the service advertisement depends on the priority of the registered services and the actual channel load. Optionally, if a user needs to inform the provider which services are installed and in which context they should run, a MAC unicast Service Context Frame (SCF) frame is returned to the service provider.

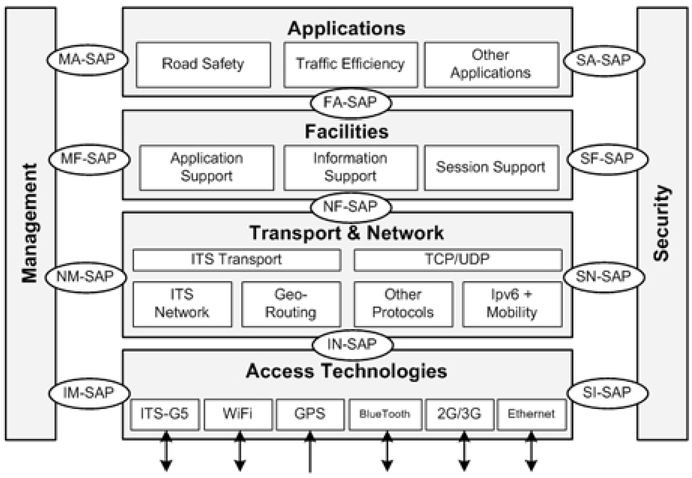


Figure 2.6: ETSI ITS architecture (copied from [40])

Furthermore, after initialization, service provider and service user may exchange MAC unicast based information and network address information.

ETSI reference architecture

At the European level, the organisation ETSI is responsible for the standardization in the telecommunications sector. In 2003, ETSI defined that ITS is an emerging topic within ETSI. Currently the ETSI activities that are considered are the ones accomplished in the five ETSI Technical Committee (TC) ITS Working Groups (WGs) are; WG1, which describes the basic set of application requirements; WG2, which provides the architecture specification; WG3, which provides the 5.9 GHz network and transport protocols; WG4, which provides the European profile investigation of IEEE 802.11p, and; WG5, which provides the security architecture [56].
Mainly based on recommendations of the COMeSafety project, ETSI standardized the main reference architecture illustrated in figure 2.6. The ITS station reference architecture explains the functionality contained in the aforementioned ITS stations. It follows the principles of the OSI model for layered communication protocols which is extended for inclusion of ITS applications [40].

The protocol stack of this protocol architecture consists of four horizontal layers: 1) applications, 2) facilities, 3) networking&transport layer, and 4) access technologies. In addition, it is flanked by a management layer and a security layer management.
There exists a variety of applications developed to run at the application layer such as co-operative traffic monitoring, control of traffic flows, blind crossing, prevention of collisions, nearby information services, and real-time detour routes computation. These applications can be classified as: active road safety applications, traffic efficiency management applications, and infotainment applications [42]. Active road safety applications support services such as lane departure warnings, speed management, headway management, ghost driver management, hazard detection, and several other similar services. Traffic efficiency applications support services such as urban traffic management, lane management, traffic flow optimization, and priority for selected vehicle types (e.g., buses, emergency vehicles). Infotainment services include pre-trip and on-trip journey planning, travel information, and location-based services. There are hundreds of different use cases considered and developed within the different projects. They all can be mapped onto one of these application classes.
The facilities layer comprises the second horizontal layer and is integrated between the application layer and the network&transport layer. The facilities layer features service access points to the management layer and the security layer. It provides facilities for applications, information and communication which can be accessed by ITS-based applications, as well as IP-based applications. To provide consolidated information about the environment of an ITS station, the Local Dynamic Map (LDM) provides data

models to represent both dynamic information and static information. Such maps may include lane-specific information including curbs, pedestrian walking, bicycle paths and road furniture such as traffic signs and traffic lights. Furthermore, all dynamic objects that are directly sensed or indicated by other road users by means of cooperative awareness messages may be referenced in such a LDM [40].
The third horizontal layer is the network&transport layer which provides services for the layers above it and utilizes the capabilities of the underlying access technologies. The objective of the network and transport layer is the transport of data between source and destination ITS stations; either directly or multi-hop through intermediate ITS stations.
The ETSI reference architecture's access technologies layer reflects CALM's objective to allow seamless communication over several coexisting radio access technologies. Both wired and wireless access technologies are supported for station-external and station-internal use. However, the architecture so far only describes wireless access technologies, in other words, different types of radio systems [62].
The management layer is a transversal layer handling cross-layer information exchange among the horizontal layers. The main functionalities implemented in this block include the dynamic selection of the access technology for a given application, the monitoring of communication interfaces' parameters, the management of transmission permissions and priorities, the management of services, and the implementation of congestion control mechanisms.
Finally, the security layer is the block implementing security services for the communication protocol stack and the management layer [11].

This section gave an introduction to ITS. The next section of will take a close look on the type of network and communication patterns used in the field of vehicular cooperative ITSs.

2.2 Data dissemination in a vehicular environment

Vehicular Ad-Hoc Networks (VANETs) are emerging new technologies to integrate the capabilities of new generation wireless networks to vehicles. The idea is to provide ubiquitous connectivity on the road to mobile users and to provide efficient V2V communications that enable the ITSs.
ITS is the major application of VANETs. As described in the previous section 2.1, ITS includes a variety of applications such as co-operative traffic monitoring, control of traffic flows, blind crossing, prevention of collisions, nearby information services, and real-time detour routes computation. Because of the high nodes mobility and unreliable channel conditions, VANETs have their unique characteristics which pose many challenging research issues, such as data dissemination, data sharing, and security issues.
In this section, we mainly focus on the dissemination aspects of VANETs in order to explain the characteristics of VANETs. First we start with a general description of VANETs. Then we continue with an identification of the frequently used communicating patterns in the field of vehicular cooperative ITSs. section 2.2.3 until section 2.2.6 comprise the communicating patterns.

2.2.1 VANETs

Wireless communication among nearby vehicles and fixed equipment along the road, referred as VANET could be considered as an instantiation of Mobile Ad-Hoc NETwork (MANET). MANETs have no fixed infrastructure and instead rely on ordinary nodes to perform routing of messages and network management functions. Besides the similarities between VANETs and MANETs, such as short radio transmission range, self-organizing and low bandwidth, their behaviour is fundamentally different due the unique characteristics of VANETS.
Driver behaviour, constraints on mobility, and high velocities create unique characteristics in VANETs. These characteristics have important implications for design decisions in these networks. In particular, VANETs differ from typical MANET models in a couple of ways.
First, they are characterized by high but somewhat predictable topology changes. Vehicles driving nearby each other forms a network topology whereas each vehicles represents a node. Vehicles on the road are likely to move with different speed and different directions, causing a highly changing topology, especially in urban areas. On the other hand, the vehicles are restricted by the boundaries of the road network and traffic rules, which make topology changes in some way predictable. The latter offers possibilities

for routing algorithm based on predictions in topology changes.
Secondly, in contrast to for example a MANET of sensor nodes, nodes in VANETs are not subject to power and storage limitation. Vehicles contain (mostly) sufficient space and include a continuously recharged battery which can result in more computing power.
VANETs are usually equipped with different kinds of on-board sensors which allows the development of advanced routing mechanisms. For example, most vehicles will be equipped with a GPS sensor which offers useful information for routing purposes[65].

2.2.2 Communication patterns in ITSs

This section includes a description of the communication in ITSs from a networking point of view. In other words, we describe communication patterns commonly used by automotive applications in the field of ITS.

Based on the results of different European consortia and R&D projects, the standardization organisation ETSI defined the Basic Set of Applications [42]. The report includes a large catalogue of use cases with related communication modes and additional requirements. Each use case includes a limited set of communication networks, selected from the currently available communication networks for ITS: V2V, V2I and I2V communications in the V2X dedicated frequency band, cellular networks (e.g., 2th-generation [23], 3th-generation [24], 4th-generation [25]) and broadcasting systems (e.g., Digital Audio Broadcasting [26], Digital Video Broadcasting [27]).

Based on the type of communication network, we define the following communication modes of operation:

- **Local ad-hoc communication** includes the scenarios with respect to ad-hoc communication, i.e. without the support of widely deployed infrastructure except the use of local communication infrastructure nodes (RSUs). This includes V2V communication, V2I and I2V communication as defined in [42]. This type of inter-vehicle communication use a VANET as the underlying network.
- **Infrastructure-based communication** covers the scenarios which communicates via a communication infrastructure network, e.g., UMTS [73], IEEE 802.16 [21] and Digital Video Broadcasting. This type of communication mostly involves backbone communication, e.g. internet or a Traffic Management Center (known as TMC, a centre that coordinates the traffic). As depicted in figure 2.7 this mode involves both broadcast and point-to-point communication.

A general overview of the communication scenarios is presented in figure 2.7:

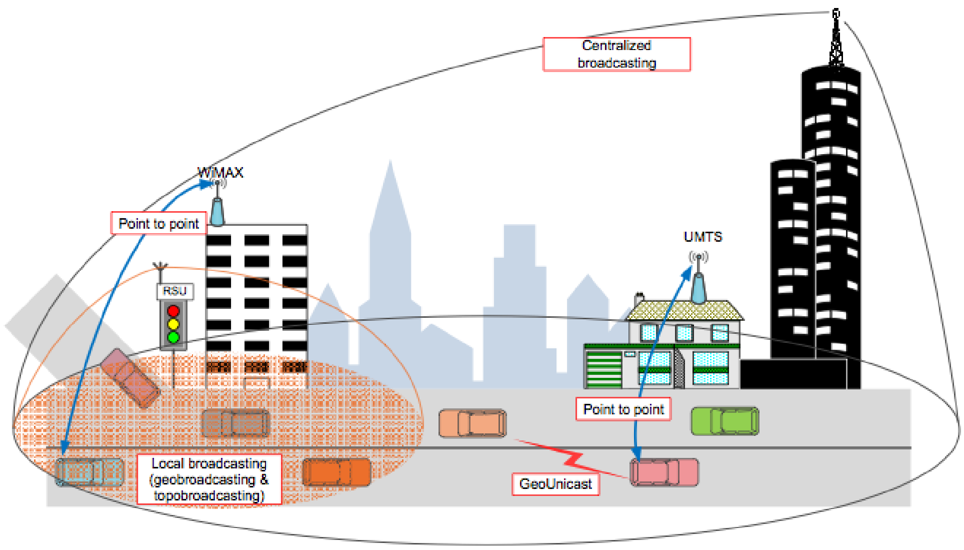


Figure 2.7: ITS scenarios (copied from [54])

Infrastructure-based communication involves a central authority to coordinate the communication of the participating nodes. Some technologies (e.g. UMTS) even require the existence of a largely deployed infrastructure.
As mentioned in the introduction section 1, this research focuses on local ad-hoc communication, and in particular the IEEE 802.11p/ITS-G5 technology. Because of 802.11p's high potential of worldwide deployment, we restrict our research to the 802.11p technology. Nevertheless, research on the potential advantages of other wireless technologies can be an interesting topic for future research.

Most of the illustrated use cases in [42] recommend a local ad-hoc communication mode. However, the operation of the use cases is usually not described in detail (i.e., it is open how data is collected, communicated, and evaluated to implement the application). For a description of the local ad-hoc communication modes we adopt the list of [76] and [30]. In these studies, the writers identified the communication patterns of several VANET scenarios and finally classified these patterns into a small set of types. These communication patterns are recurring patterns with multiple similar characteristics which eventually can be used for the design of VANET-based communication system.

Every VANET application is at least characterized by: (1) a Zone Of Interest (ZOI), (2) an application trigger condition and (3) a reception pattern [30]. Before listing the communication patterns, we start with an illustration of these terms. It should be noted that although the 802.11p technology is likely to be world-wide deployed in VANETs, their classification is independent of the actual communication technology and assumes only the availability of a link-layer mechanism.
The first application characteristic *ZOI* is the size of the geographical region covered by those entities participating in an application. Different kinds of applications have different ZOI sizes. For example, in some safety applications, vehicles need to be aware of the kinematics status of other vehicles in their direct neighbourhood (i.e., a few hundred meters), whereas in other safety applications vehicles need to know the hazard situation of a stretch of road that lies ahead.
A second application characteristic is the *trigger condition*: the circumstances of how applications are triggered. This is either *periodic*, *event-driven*, or *user-initiated*. Examples of these kinds of applications are respectively a periodic broadcast of collision warning messages, an event based brake message and parking lot availability request message.
Thirdly, applications can be characterized by their *reception pattern* of application messages. This specifies the pattern of potential message recipients for an event, which varies between applications. For instance, in safety applications in which a vehicle disseminates a cooperative collision warning in case it notices a collision, it is critical for all neighbouring vehicles to hear the broadcasted safety alert messages to avoid potential collisions (a *one-to-many* pattern), whereas for safety applications in which vehicles disseminate a braking notification, only vehicles in the region being affected (vehicles behind the event originator) need to hear the safety alert message (a *one-to-a-zone* pattern). Likewise, a *point-to-point* communication pattern is often used in many convenience and commercial applications, and a *many-to-one* pattern is also sometimes used. Thus, the pattern of event message recipients can be grouped into four categories: *one-to-many*, *one-to-a-zone*, *one-to-one*, and *many-to-one*.

Multi-hop data dissemination capability is one of the major advantages of VANETs. When the message needs to be disseminated to the vehicles beyond the transmission range, multi-hop is used. Accordingly, multi-hop data flows in a VANET could result from a range of applications and can have a major influence on the design of the data dissemination technologies. Multi-hop data dissemination requires in general: the knowledge of node locations, and a method of forwarding packets toward their destinations [33]. This may be accomplished by two types of technologies: a routing protocol that performs both functions (maintaining the network topology and forwarding packets along shortest paths), or by a combination of location service and a method of packet forwarding.

The classification in [76] identifies the following communication patterns: geo-broadcast, geo-unicast, beaconing, advanced information dissemination and information aggregation. Both geo-broadcast, geo-unicast will be explained in the context of geocast. Then, we continue with an description of the other communication patterns.

2.2.3 Geocast

Geocast is a form of geographic multicast wherein the destination nodes are selected based on their geographic position [66]. Many applications defined in [41] use a form of geocast to disseminate the Decentralized Environmental Notification Message (DENM), a time-restricted message that provides information about a location based situation
The geocast addressing scheme employs two types of geographic addresses: individual node addresses that are linked to the physical geographical position of the node, and geographical regions based on geometric shapes (such as circles, rectangles). A geographical address contains a time significance, due to the continuous movement of a vehicle [31].
Geocast distinguishes among three basic forwarding types to forward packets as part of a routing protocol: geo-broadcast, geo-anycast and geo-unicast. The different forwarding protocols are discussed in the following sections.

Geo-unicast routing

With unicast there exists a peer-to-peer communication link between a sending station and receiving station. The link may consists of more than one hop, which require the existence of a multi-hop routing scheme. Multi-hop routing in VANETs is significantly complicated owing to the partitioned nature of the networks resulting in highly unstable paths and only a number of routing schemes for ad-hoc networks can be considered suitable [33]. Position-based routing approaches have shown superior performance in contrast to topology-based approaches due to their adaptability to the high node movement dynamics in VANETs. Position-based routing require a location service which maps nodes to a geographical position and a forwarding scheme which selects the next hop based on the geographical information of the node, neighbours, destination, and other mobility parameters.
In many cases the applications that use the unicast routing mechanism send their packets upon system internal events or because of manual user interaction [76]. Using geocast routing as the type of routing protocols for VANETs has the advantage that vehicles outside the area are not alerted to avoid unnecessary hasty reactions.

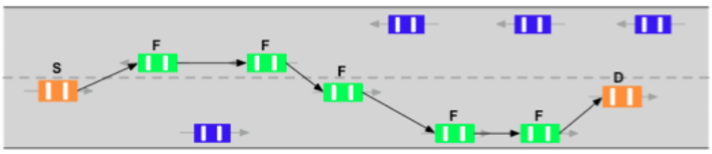


Figure 2.8: Geo-unicast (copied from [31])

Geo-broadcast

Geo-broadcast uses the concept aforementioned concept of ZOI which represents the destination nodes inside the specified geographical region of a source node (which is usually also inside the ZOI). Geocast routing can be considered as multicast service within a specific geographic region. Inside the ZOI an efficient flooding protocol can be used to forward the packets. Figure 2.9 depicts the geo-broadcast mechanism. The geographic region is determined by a rectangular shape.

The scenario depicted in figure 2.9 includes a source node which is located inside the ZOI. This is the common case for safety applications in which a vehicle addresses all others vehicles in the opposite driving direction. Though there exists a second senario in which the source node is located outside the ZOI. As depicted in figure 2.10, the data packets are forwarded by means of a geo-unicast protocol towards the ZOI.

Because of the multi-hop nature of vehicular networks, flooding is a fundamental mechanism to implement the multi-hop broadcasting. With flooding, each node re-broadcasts messages to all of its neighbours except the one it got this message from. Flooding performs relatively well for a limited small number

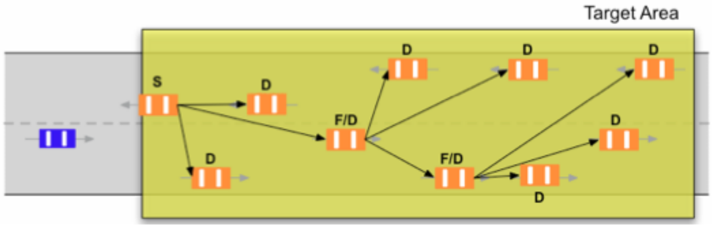


Figure 2.9: Geo-broadcast (copied from [31])

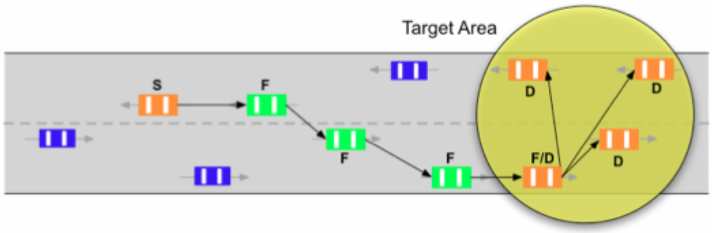


Figure 2.10: Geo-broadcast with packet transport towards the target area (copied from [31])

of nodes, but when the number of participating nodes in the network increases, the performance can drop quickly. As each node receives and broadcasts the message almost at the same time, this causes contentions and collisions. To alleviate this phenomenon, also known as broadcast-storm, most of geo-broadcasting protocols developed for vehicular networks include efficient flooding methods; i.e., only a limited number of nodes relay the broadcasting data.

The different proposed geo-broadcast protocols mainly differer in whether they are based on flooding, directed flooding or on routing without flooding. Direct flooding tries to limit the message overhead and network congestion of normal flooding by defining a forwarding zone and restricting the flooding inside. Routing without flooding is based on unicast.

Geo-broadcast messages are typically sent upon a certain external event, or, in other words, geo-broadcast messages are not sent continuously, although messages with the same content may be repeated from time to time (e.g., in case of a work zone warning) [76].

Geo-anycast routing

Geo-anycast transports data from a single node to any of the nodes within a geographical area. Compared to geo-broadcast, with geo-anycast a packet is not forwarded inside of the geographic area when the packet has reached the destination area.

2.2.4 Beaconing

Beaconing is the continuous update of information among all neighbouring nodes [76]. One of the most well known examples of beaconing in VANETs is the dissemination of the **Cooperative Awareness Message** (CAM), nearly used in every VANET scenario and lately standardized by ETSI in [39]. The CAM payload contains vehicle status information such as position, speed and heading to allow cooperative awareness. By receiving CAMs, an ITS station is aware of other stations in its neighbourhood area as well as their positions, movement, basic attributes and basic sensor information. At the receiver side, reasonable efforts can be taken to evaluate the relevance of the messages and the information. This allows ITS stations to get information about its situation and act accordingly. An interesting note is that the CAM beaconing mechanism resides not on the application layer, but is integrated in the management

layer of the architecture [39]
Data packets are send as link layer broadcasts to all neighbours in the reception range. The CAM payload size is relative small in contrast to the packet size of for example infotainment applications. Although not restricted, typical used beacon size ranges from 400 to 500 bytes (including security overhead) [74]. All stations in the near field of the sending station form the ZOI. A typically used communication range is 250 m, thus with the maximum communication ranges of 1000 m of the 802.11p technology single-hop communication is sufficient to disseminate the CAMs.

Most of the applications that are characterized by a beacon communication pattern send their data packets on a periodic basis. In a few cases the beaconing mechanism may be started by an external trigger (e.g. if an accident occurred), but in such a case, the information may just be added to the regular packets of the beaconing application.

Beaconing can be seen as a specific case of topologically-broadcast. Topologically broadcast is a forwarding mechanism that is restricted by the number of hops, e.g. the number of hops of in figure 2.11 is restricted to two hops. In this context, beaconing concerns topologically broadcast with a scope of one hop.

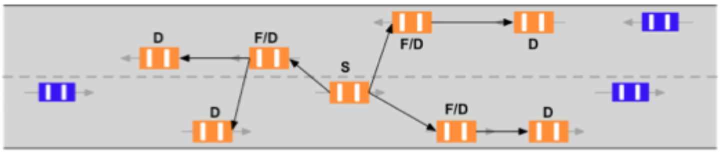


Figure 2.11: Topology-broadcast (copied from [31])

2.2.5 Advanced information dissemination

Advanced information dissemination is the dissemination of information among vehicles during a certain time, capable of bridging network partitions and prioritizing information [76]. The goal is to provide information to vehicles that arrive later in time and previously could not be reached due to network partitioning. In addition, the bandwidth usage should be scaled to the priority of messages in the current context of a vehicle (i.e., dissemination should send only messages with high priority when bandwidth is scarce).
Schemes for this pattern usually use single-hop broadcasts while resending the message for a limited amount of time. For example, the proposed advanced information dissemination scheme in [61] uses a context relevance mechanism in order to determine which message should be send over the wireless medium. The sender does not specify a destination, but information is spread according to its contextual relevance instead.

2.2.6 Information aggregation

In contrast to the other communication patterns, with information aggregation the nodes actually process and merge the data. Although all these patterns pursue the same goal (i.e., to spread information among nodes), communication overhead can be reduced when events are detected by multiple nodes. Additionally the information aggregation can improve information quality when, for example, nodes detect a traffic jam and each node contributes some information about a part of the traffic jam.
The communication mechanism for this type of dissemination pattern can be diverse, ranging from periodically single-hop communication to request based multi-hop communication. Messages as such are not forwarded by the receiver; instead, incoming information only contributes to the local knowledge base from which new messages with merged information are created.
Most of the applications that are characterized by a information aggregation communication pattern send

their packets on the trigger of an event (e.g., in case of the detection of a traffic jam), although some applications exchange data periodically (e.g. as with a city wide parking lot application) [76].

In this section, commonly seen communication patterns in VANETs has been discussed. Most details about VANET were described and a comparison with related systems has been made.
In the next section, we will discuss the use of wireless LAN in such a vehicular environment.

2.3 Wireless LAN in a vehicular environment

Among the different candidates for the standard wireless technique for VANET communication, the recently standardized Wireless Local Area Network (WLAN) amendment 802.11p is gaining high popularity. Based on the WLAN 802.11 standard, the IEEE standardization body published the 802.11p as an amendment for the vehicular environment.
This section describes WLAN in the context of VANETs. First we start with a description of the modes of operation of IEEE 802.11 in general. The second part of this section comprises the IEEE 802.11p amendment for WLAN in a vehicular environment.

2.3.1 IEEE 802.11

IEEE 802.11 is a set of standards for implementing WLAN communication in the 2.4 GHz, 3.6 GHz and 5 GHz frequency bands. They are created and maintained by the IEEE LAN/MAN Standards Committee (IEEE 802). The base current version of the standard is IEEE 802.11-2007 [49].
The 802.11 family consists of a series of over-the-air modulation techniques that use the same basic protocol. The most popular are those defined by the 802.11b and 802.11g standards, which are amendments to the original standard. Although originated as 802.11-1997, the first widely accepted one was 802.11b, followed by 802.11g and 802.11n. Security was originally purposefully weak due to export requirements of some governments, and was later enhanced via the 802.11i amendment after governmental and legislative changes. Other standards in the 802.11 family are service amendments and extensions of or corrections on the previous specifications.

All the 802.11 standards comprises the two lowest layers of the OSI model: the Physical (PHY) layer and the Medium Access Control (MAC) layer. Basically, the MAC layer is responsible for the medium access mechanism, the PHY layer handles the details of medium transmission and reception.
The 802.11 wireless networks can exhibit two different basic system architectures: infrastructure-based and ad-hoc. In the following we briefly describe the basic concepts of these two wireless modes [44].

Infrastructure-based 802.11 networks

An infrastructure IEEE 802.11 WLAN is based on cellular architecture where the system is subdivided into cells, in which each cell forms a **Basic Service Set** (BSS) that is controlled by a the central authority: **Access Point** (in short AP, also called base station). All the nodes, called **Stations** (STA), within the same radio coverage belong to one BSS.
Multiple BSSs which belong to the same network are connected by the APs via a Distribution System (DS). Rather than prescribing the exact architecture of such a DS, the IEEE 802.11 standard [49] describes different DSs on the service, denoted as Distribution System Services (DSSs). The whole interconnected WLAN - including the different cells, their respective APs and the DS - is seen to the upper layers of the OSI model, as a single IEEE 802 network denoted as the **Extended Service Set** (ESS). The WLAN has its own identifier, named ESSID, which is used by STAs to participate to the wireless network. The 802.11 WLAN is connected to another 802 WLAN through a portal, which is specified by the standard as an abstract description of the translation functionality to traditional LAN.

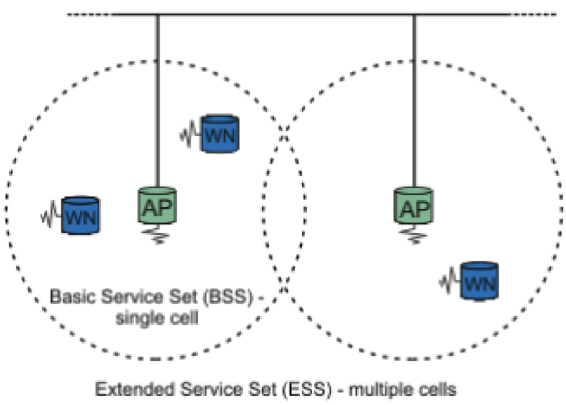


Figure 2.12: BSS and EBSS in infrastructure-based 802.11 networks

Ad-hoc wireless 802.11 networks

In addition to the infrastructure mode, IEEE 802.11 defines the **Independent BSS** (IBSS) for wireless ad-hoc mode of operation. In certain circumstances it is desired to build up WLAN networks without APs, e.g. in case of the communication of an event message between two vehicles (STAs). In this case, an IBSS compromises a group of stations using the same radio frequency. Part of the AP functionality is performed by the STAs (like beacon generation, synchronization, etc), and other functions are not supported (like routing, forwarding, frame-relaying, power saving).

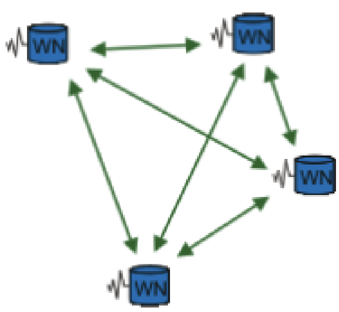


Figure 2.13: IBSS in ad-hoc wireless 802.11 networks

Access schemes

As a solution to share the same radio frequency of one BSS between STAs, [49] defines the Carrier Sense Multiple Access/ Collision Avoidance (CSMA/CA) mechanism. The basic idea of CSMA (without CA) is to provide a shared access method: before accessing the medium, a STA should sense the carrier (i.e., the medium) and if the medium is busy, the STA will defer its transmission to a later time, otherwise the STA will ium. A STA tries to avoid collisions as much as possible, though it is absolutely not guaranteed the collisions may occur. The extended version of CSMA with CA combines sensing of the carrier with a windows based *back-off scheme* in case a STA encounters a busy medium.
The basic access method for both described modes is handled by the Distributed Coordination Function (DCF). DCF is the foundation of PCF but can also be used by itself, primarily when there is no central authority (Access Point) present.

The DCF operates as follows. When a STA wants to transmit some data, it senses the medium. It is the responsibility of the PHY layer to sense the carrier and provide a Clear Channel Assessment (CCA) to the MAC layer in case it senses an idle medium. If the medium is idle for a minimum amount of time (known as the DIFS), the STA is allowed to access the medium at once. This allows short access delay under light load. In case of unicast data transfer, a receiving STA respond with a ACK message after waiting the minimum time of one SIFS. Other stations still have to wait a least for a period of one DIFS which is a longer time interval than the SIFS waiting time. Figure 2.14 illustrates the operation of the DCF.

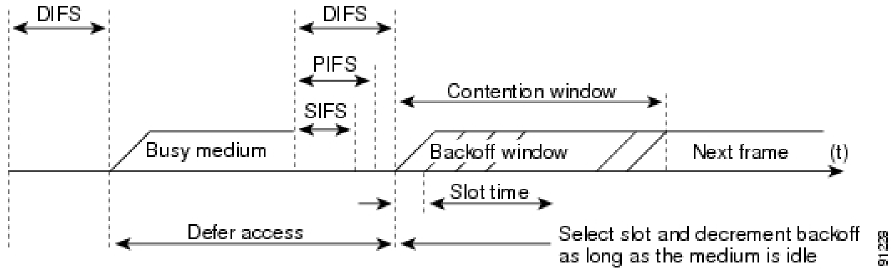


Figure 2.14: DCF basic access method (copied from [49])

Subsequently, if other STAs have data ready to send, they not only have to wait a period of one DIFS after sensing an idle medium again, but additional a random *backoff-timer* is added to the total waiting time. The random back-off timer is a randomly chosen waiting time within the contention window. Fairness is guaranteed by pausing the back-off timer in case of sensing a busy medium, the remainder of the back timer is added to the DIFS waiting time in the next waiting cycle as soon as the random backoff timer expires, the STA accesses the medium.

2.3.2 IEEE 802.11p/ITS-G5 technology

The protocol IEEE 802.11p [50] is an amendment of the IEEE 802.11-2007 [49] protocol for wireless networks which focuses on the improvement of the performance of the CSMA/CA networks in highly mobile ad-hoc networks. The European variant, known as the European profile for ITS in the 5 GHz band, is standardized by ETSI and is referred as ITS-G5 [43]. ITS-G5 is being developed according to the IEEE 802.11p standard, the IEEE 1609 standards and the ISO CALM standard as well.

Mode of operation

Using the previous described access method with scanning for beacons and executing multiple handshakes could be too time-consuming in case of vehicular safety communications (e.g. in a scenario where two communicating vehicles drive in opposite directions). As a solution the IEEE 802.11p standard defines the **WAVE mode** where a station is allowed to send and receive data frames with the wildcard BSSID value without the need to belong to a BSS. Thus by discarding the scanning and multiple handshakes processes STAs can immediately communicate with each other upon encounter as long as they operate in the same channel. If a STA is in WAVE mode it shall not join a infrastructure BSS or IBSS. Since data is exchanged without a distribution system both DS bits of the MAC header are set to zero.

Even for non-safety vehicular stations which want to advertise their services the additional overhead may be too time-consuming. Therefore the IEEE 802.11p standard defines the **WAVE BSS** (WBSS). A WBSS is instantiated by the upper layers above the IEEE 802.11 and sent by the initiating STA as an advertisement of a beacon frame containing the WAVE BSSID and all of the services offered in the WBSS. Receiving STAs independently decide whether to join the WBSS by only receiving the advertisement with no further interactions.

The wildcard BSSID is also supported if a STA already belongs to a WBSS, thus a STA can send information to all neighbouring STAs even if they do not belong to the WBSS. Since an initiating STA of a WBSS is no different from any other member of the WBSS, a WBSS can continue if the initiating member quits the WBSS [20].

Within the context of V2I and I2V IEEE 802.11p/ITS-G5 communication, the infrastructure nodes behave as ad-hoc peer stations with, from a functional point of view, equal characteristics as mobile nodes. In this mode, infrastructure nodes are used to connect the vehicles to backbone networks or to enhance the communication range between vehicles.

As discussed, the focus of the amendment is on simplifying the standard BSS operations in a truly ad-hoc manner for vehicular usage. The described mode of operation is basically handled by the medium access layer, which employs the CSMA/CA medium access mechanism for channel access.

Physical layer

The physical layer of IEEE 802.11p is essentially based on the Orthogonal Frequency Division Multiplexing (OFDM) physical layer of IEEE 802.11a. Changes to the physical layer should be, according to the amendment IEEE 802.11p, at a minimum level in order to avoid the design of a entirely new wireless air-link technology. To handle the specific vehicular channel characteristics like dynamically changing influences of multi-path interference and shadowing the physical layer uses OFDM with some minimalistic changes. section 2.5 explains the physical influences on the vehicular channel in more detail.
The IEEE 802.11p spectrum is structured into seven 10 MHz wide channels and can be implemented with open off-the-shelf chip sets and software. Choosing 10 MHz wide channels instead of the usual 20 MHz of IEEE 802.11a introduces a longer guard interval which addresses better the worst case delay spread created by multipaths. Halving the channel bands is accomplished by doubling of all OFDM timing parameters, but as a consequence all the data rates are halved.
The European profile divides the spectrum into three modes of operation, with the ITS-G5A as the operation mode dedicated to ITS for safety and traffic efficiency related applications.
The ITS-G5A mode operates in the 5875-5905 MHz frequency band with 10 MHz wide channels as showed in table 2.1.

Channel type	Centre frequency	IEEE channel	Data rate	TX power limit
G5CC	5,9 GHz	180	6 Mbit/s	33 dBm EIRP (2 W)
G5SC2	5,89 GHz	178	12 Mbit/s	23 dBm EIRP (2 mW)
G5SC1	5,88 GHz	176	6 Mbit/s	33 dBm EIRP (2 W)

Table 2.1: ITS-G5A channels

QoS

Besides the simplified BSS operations, the 802.11p standard describes priority and QoS differentiation in order to handle the requirements of the different types of applications. For this purpose, the Enhanced Distributed Channel Access (EDCA) mechanism of the IEEE 802.11e [29] standard is reused.
To ensure the medium access priority, there are different Arbitrary Inter-Frame Spacing (AIFS) and Contention Windows (CWs) defined for each Application Category (AC) (i.e., the QoS level). Table 2.2 summarizes the default EDCA parameter settings used in IEEE 802.11p, where 1 denotes the highest priority level and 4 the lowest.
Within QoS classes the collisions are not prevented by the EDCA. After a packet collision has occurred, a backoff time is randomly chosen from the CW interval. The CW size is also inherent to the priority level, giving high priority packets the higher probability of channel access after a collision. The initial size of the CW is given by the factor CWmin. Each time a transmission attempt fails, the CW size is doubled until reaching the size given by the parameter CWmax.

Several performance studies (e.g., [37, 82]) have focused on the evaluation of the EDCA QoS extension supported by the 802.11p protocol.

AC	CWmin	CWmax	AIFSN
4	15	1023	9
3	15	1023	6
2	7	15	3
1	3	7	2

Table 2.2: EDCA parameter settings for different application categories in IEEE 802.11p

In [37] it is shown by simulation and analytical means that the use of highly prioritized messages could lead to a significant increase of the collision probability, especially in dense V2X communication scenarios. To handle this problem, the writers suggested the use of a re-evaluation method - proposed in a previous work- whose objective is to reduce the number of high priority messages and prevent long message queues.
In [82] the writers showed that fixing the size of the backoff window in EDCA could decrease the throughput in V2I communication scenarios. Therefore, they have proposed two approaches (a centralized and a distributed one) to adapt the size of the back off window to the number of communicating vehicles.

2.4 VANET simulation

There are three main techniques to analyse the behaviour of a system: analytical modelling, computer simulations and real time physical measurements. Several studies started to create analytical models of the wireless communication for VANET scenarios, particularly theoretical models of the IEEE 802.11p standard haven been developed [48, 81, 58, 55]. On the other hand some researchers constructed IEEE 802.11p hardware (mostly based on IEEE 802.11a hardware) and assessed the performance of the wireless system by conducting several field tests [34, 72]. Despite the potential of field tests to get first insights into the benefits and problems faced in the development of wireless vehicular cooperative systems there is yet the need to evaluate them in the long term and at large scale.
A simulation environment offers an approach to test new technologies in a controlled environment. Without the need to acquire hardware, large scale testing is relative inexpensive and the integrated simulator allows the quantitative analysis of both traffic and wireless networks.
A commonly used approach to implement a simulator is Discrete Event Simulation (DES). In contrast to Time Driven Simulation (TDS), which simulates every time step, DES is based on an event scheduler and only calculates the impact of those events, thereby saving simulation time. For example, the simulation of a vehicle moving at a certain speed along a road can be simulated continuously or either configured as an event corresponding to the next instant that the vehicle has to modify its movement, saving a considerable amount of simulation time and computer resources.

This section explains the concepts of VANET simulation by describing the basic components of a VANET simulator. We provide certainly not comprehensive list of available simulators, though we will mention some existing simulators. The second part of this section briefly describes the DES VANET simulator iTETRIS, which we have been using during our research. In order to understand the concepts of VANET simulation, we start with a description of the main two components of a VANET simulator: the mobility simulator and the network simulator.

2.4.1 Overview

Existing simulation software used in VANET related studies can be classified to one of the following categories: VANET simulators, network simulators and vehicle mobility simulators (i.e., traffic simulators) [68]. Vehicular mobility generators are needed to increase the level of realism in VANET-and network simulations. They generate realistic vehicular mobility traces to be used as input for a network simulator. The inputs of the mobility generator include the road model, and scenario parameters (i.e., maximum vehicular speed, rates of vehicle arrivals and departures, etc). The output of the trace details the location of each vehicle at every time instant for the entire simulation time and their mobility profiles. Examples

of vehicle mobility simulators are SUMO [63] and VISSIM [4].
Network simulators are used to simulate and then analyse the effect of various parameters on the network performance. It includes all aspects of wireless communication: transmission, reception, background load, routing, channel allocation, etc. Examples are ns2/3 [13], GloMoSim [9] and OMNeT++ [14]. Most network simulators contain by default several wireless modules, however with the rise of VANET research, the research industry needed integration with mobility generators in order to increase the level of realism.
Finally, VANET simulators consist of integrated network and mobility simulators. Examples of VANET simulators are iTETRIS [11], GrooveNet [10], TraNS [19], VSimRTI [10].
In the next few sections describe the characteristics of vehicle mobility simulators, network simulators and VANET simulators.

Vehicle mobility simulators

Mobility simulators classification ranges from sub-microscopic to macroscopic depending on the level of detail of the simulation. This is reflected on the smallest entity considered by the simulator. Macroscopic simulators consider the whole traffic flow as the basic entity.
On the other hand, microscopic simulation considers the vehicle the smallest simulation unit. There are simulators which are in-between macroscopic and microscopic, referred as mesoscopic. The latter consider individual vehicles moving between queues, which are the main simulated entity. There are also sub-microscopic simulators which consider not only each vehicle, but also the components of them, as the engine or the gear-box, and their parameters.

One of the most well known open source mobility simulator is Simulation of Urban MObility (SUMO) [63]. SUMO is a microscopic, space-continuous, and time-discrete traffic flow open source mobility simulator. SUMO incorporates realistic traffic simulation algorithms, with the possibility to have different types of vehicles, different networks and has a high speed performance. By default it incorporates not only the mobility simulator SUMO, but also a bundle of applications including a Graphical User-Interface (GUIs) to enhance the generation of networks as well as the import/export capabilities of the software. This tool is of interest for the VANET research community mainly because [57] developed the Mobility Model Generator for Vehicular Networks (MOVE) tool, which stands over SUMO and includes some GUIs to facilitate the process of road topology and vehicular mobility definition, as well as output traces converters for network simulators.

For VANET simulations, where every individual vehicle will be considered a node and the simulation of the vehicle components and their status are not relevant, the most adequate approach to mobility simulation is microscopic. It provides enough resolution of the system as to provide realistic traces, but without the overload of simulating sub-microscopic details which would not provide relevant information for this research.

Network simulators

Compared to the cost and time involved in setting up an entire testbed containing multiple networked computers, routers and data links, network simulators are relatively fast and inexpensive. Network simulators are particularly useful to test new network protocols or to propose modifications to existing ones in a controllable and reproducible way [68].

Ns (from network simulator) is a name for series of discrete event network simulators, specifically ns-2 and ns-3. Both simulators are used in the simulation of routing protocols, among others, and are heavily used in ad-hoc networking research, and support popular network protocols, offering simulation results for wired and wireless networks alike. After the critics on the ns-2 simulator, the network simulator community started around the year 2006 with the development of ns-3 simulator. Because of the decision to move from OTcl scripting language to the C++ and Python programming language, backwards compatibility to ns-2 is not guaranteed. The project started making quarterly software releases in 2008 and recently made its tenth release (ns-3.10) in the beginning of this year.

VANET simulators

One important aspect in a simulation model for a VANET system is the drivers response to the application. The reaction of drivers in different situations could affect traffic throughput. For example, a driver who receives a collision warning message can either hit the brake or exit the highway, depending on the distance to the accident scene and the availability of exits.
The software that allows one to change the behaviour of vehicles (depending on a given application context) is known as an integrated framework or simply a VANET simulator [68]. Currently, the mobility and network models in integrated frameworks are implemented in two separated simulation tools. The next section illustrates the concept of VANET simulators with a description of the VANET simulator iTETRIS.

2.4.2 iTETRIS: an integrated network and traffic simulator

To ensure the efficiency of cooperative vehicular ICT systems, it is crucial that the communication protocols are adequately designed and optimised, and that the applications using such communication capabilities are tested under realistic conditions. In this context, the European FP7 iTETRIS project created the *iTETRIS simulation platform* to allow for a realistic and accurate evaluation of the design and impact of cooperative vehicular communication systems and traffic management policies under realistic large-scale scenarios [64].
This section covers the iTETRIS platform in short in order to understand the general concepts and operations. We start wit a clear overview of the main building blocks and the general mode of operation. Mainly because our research analysis mainly focuses on the wireless communication, we discuss the iTETRIS customization of the ns-3 network simulator into more detail.

Architecture overview

The iTETRIS architecture has been developed in line with the ITS standardization results of the European standardization organisation ETSI. In particular, the building blocks of the ETSI architecture depicted in 2.6 have been implemented with the exception of the security block and several access technologies. As a result, the alignment of the iTETRIS platform with the major international and research standardisation efforts in ITS is assured [53].
Figure 2.15 shows the iTETRIS platform with the three main building blocks: SUMO simulator, NS-3 simulator and the integration block integrated Control System (iCS). The central block is iCS which, apart from providing a coupling and controlling entity between the two types of simulators, provides an user interface to the traffic management applications. The modular set up allows platform specific developers to autonomously develop additional functionality for both simulators, while at the same time traffic engineers can add new traffic applications on their preferred platform. In theory, it is even possible to connect a total new traffic or wireless simulator to the iCS intermediate component [53].

The main contribution of the iCS block, and the iTETRIS platform in general, is the facility functionality which is aligned with the facilities layer illustrated in the ETSI architecture of section 2.1.2. The facility functionality supports functions to applications, information management and high layer message exchange protocols. Furthermore it includes the CAM support, DENM support and a complete implementation of the LDM.
With the objective to minimize the communication between the iCS block and the ns-3 block in mind, the developers implemented the communication related facilities in the ns-3 block, while application related facilities have been implemented in the iCS block.
In addition, the iCS block supports the synchronization functionality by means of synchronizing through the interfaces of the application, ns-3 and sumo blocks. Basically one iTETRIS run-time cycle is composed of (1) a ns-3 stage, (2) a sumo stage, (3) an application stage and (4) a iCS stage. The synchronization time is per second, i.e. for every simulation cycle, the integrated ns-3 and sumo simulator is allowed to run its scheduled simulation events for a time frame of one second. Thus for every iTETRIS cycle, both the SUMO and NS-3 simulator run its events for one second.

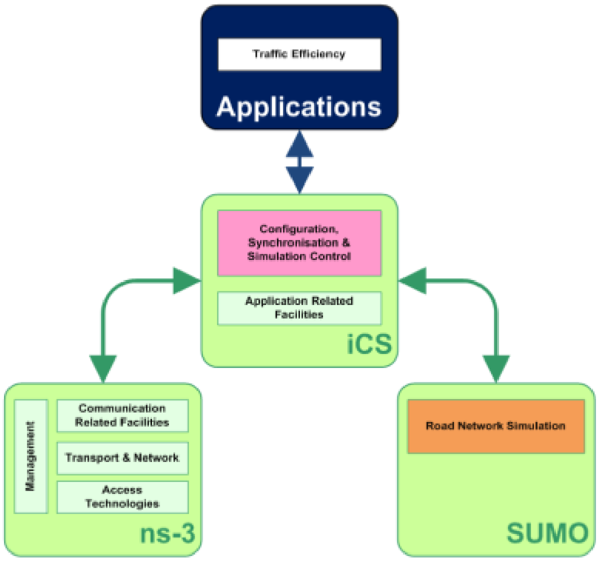


Figure 2.15: iTETRIS architecture (copied from [53])

To achieve easy application development, the iCS block has been disclosed with an API which enables applications to control both the node movement and the wireless communication. In this set up, the application is responsible for a node's sending and handling of messages, and node's movement, i.e., all the application logic. The type of applications can range from active safety, and traffic efficiency to infotainment or sustainable services. The iTETRIS project included several prototypes of applications based on the ETSI Basic Set of Applications [42].

The SUMO block includes the discrete-event-based SUMO simulator along with the Traffic Control Interface (TraCI) [63]. Due to the flexibility of the TraCI, the iTETRIS developers used the general SUMO version without the need to further adapt the software (in contrary to the customizations of the ns-3 simulator as we will see in the next section).
We end our description of the architecture with the note that at time of writing security functionality is not included in the iTETRIS platform, but may be included in the future.

Network architecture

Within the iTETRIS architecture, the ns-3 block is in charge of simulating the exchange of V2X information among the nodes (vehicles and infrastructure elements). For this purpose, ns-3 implements a set of radio access technologies (through which the iTETRIS nodes transmit and receive traffic data packets on the wireless medium) and communications stacks providing the required protocols allowing nodes to communicate with each other [54].
In contrast to ns-2, the ns-3 simulator does not include a wide variety of communication protocols and radio technologies. This may be due to the fact that the ns-3 project has made special effort on the design of a long-term well-structured simulator rather than provide many communication modules in early stages of the simulator development. Nevertheless, the iTETRIS developers used some of the ns-3 community modules to build ITS specific additions to the network layer and link layer.

As mentioned previously, the iTETRIS communication architecture is aligned with the ETSI architecture (described in section 2.1.2). The ns-3 simulator comprises the ETSI access technologies layer, transport & network layer and a part of the facilities layer. A node in ns-3 represents a vehicle or a Communication Infrastructure Unit (CIU), having installed a set of applications, communication protocols and network devices. Figure 2.16 depicts the iTETRIS architecture of an ns-3 node, with the interface to the iCS block on top of it.

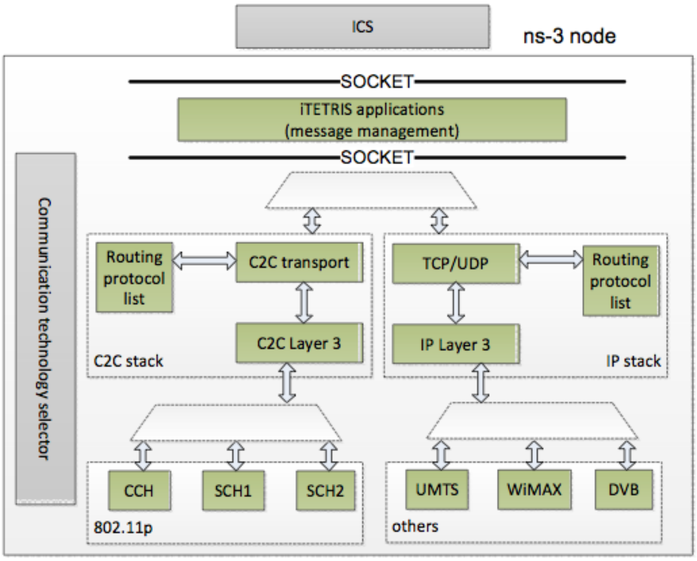


Figure 2.16: iTETRIS ns-3 node (copied from [54])

Internally, ns-3 employs the socket mechanism for inter-communication of ns-3 nodes. The iTETRIS implementation of ns-3 includes a message management facility which basically coordinates the installed applications (e.g., beaconing, traffic efficiency application) and messages. By default, ns-3 does not include a server component with the ability to control the ns-3 system. Therefore, the developers of iTETRIS constructed an interface with the ability to synchronize data with the iCS block.

The iTETRIS platform integrates three communication stacks: IPv4 stack, IPv6 stack and the iTETRIS C2C (geo-networking) stack. In particular the C2C stack is required to be implemented and integrated with existing IP stack, developed by ns-3 project. In the current ns-3 stable version, IPv4 and IPv6 functionalities are already available. Therefore, no particular efforts have been put on these TCP/IP related stacks [54]. In order to have a common and generic addressing scheme, the generic format C2CAddress has been designed to support several addressing formats (corresponding to different geo-routing schemes). For example, the geo-unicast mechanism could use a node's ID as the destination address whereas geo-broadcast mechanism uses a reference to a geographic area [54].

The ITS-G5 wireless technology introduced in section 2.3.2 has been implemented in the iTETRIS platform for V2V and V2I communications in the 5 GHz band. In particular, only the ITS-G5A operation mode has been developed given that iTETRIS is specifically focused on the evaluation of traffic management policies and hence others operation modes are not relevant for the project. However, the open and modular architecture of the iTETRIS allows the inclusion of further operation mode.
Since ITS-G5A practically relies on 802.11p which in turn is an evolution of 802.11a, the iTETRIS developers adapted an existing ns-3 WiFi network device according to the profile described in the ITS-G5 section [52]. In addition to ITS-G5, several wireless technologies have been implemented such as UMTS and IEEE 802.16 (WiMAX) [21].

To conclude this section, VANET simulation - and the iTETRIS simulator in particular - seems as a realistic tool to test larger scale ITS scenarios. The next step is to figure out how the VANET communication channel can be modelled and which radio wave propagation effects exists.

2.5 VANET channel modelling

The mobile radio channel places fundamental limitations on the performance of the wireless communication system. Regardless of the transmission technique employed, knowledge of the wireless channel is

vital to the optimal design and performance of any V2X communication system [69].
A propagation model can be used to estimate the received signal strength in case there is a clear, direct Line-Of-Sight (LOS) between transmitter and receiver.
This section will focus on radio wave propagation effects in the first section an on vehicular propagation models in the second section.

2.5.1 Radio wave propagation effects

Most VANET systems operate in urban areas where there is no direct LOS between the transmitter and the receiver, and where the presence of high-rise buildings introduces a range of radio wave propagation effect. Even in the cases of high ways with more LOS conditions, the radio signal is influenced by several propagation effects. The following paragraphs discuss some problems arising in this context.

Path loss

Path-loss represents signal attenuation and is defined as the ratio (measured in dB) of the received power to the transmitted power at certain distance from the transmitter. It describes the decrease in the received signal level with distance [52]. While in the case of LOS the path loss does not cause too much trouble for short distances, the atmosphere heavily influences transmissions over longer distances. The Free Space propagation model is used to predict received signal strength when the transmitter and receiver have a clear, unobstructed LOS-path between them. The free space power received by a receiver antenna which is separated from a radiating transmitter antenna by a distance d, is given by the *Friss free space equation*:

$$P_r = \frac{P_t \lambda}{(4\pi)^2 d^2 L} \tag{2.1}$$

where P_r is the received power, P_t is the transmitted power, d is the distance between transmitter and receiver in meters, and L is the system loss factor not related to propagation, and λ is the wavelength in meters. Antennas are assumed to have unity gain and are excluded in the formula. This formula shows that the received power falls off as the square of the distance from transmitter to receiver. This implies that the received power decays with distance at a rate of 20 dB/decade [73].

A widely used path loss model is the *Log Distance* path loss model which describes the radius of communication range. The communication range r is computed as the ratio of transmission power P_t and minimum receive threshold P_r with the inverse squirt of the path loss exponent α that characterizes the radio environment.

$$r = \sqrt[\alpha]{\frac{P_t}{P_r}} \tag{2.2}$$

Two nodes are able to communicate of the distance between the nodes is less than r. Typical path loss exponents for VANET environments range from 2 (free space) to 5 (shadowed urban environment) [73].

Additional signal propagation effects

The other basic propagation mechanisms which influences the propagation in free space of the communication between transmitter and receiver are shadowing, reflection, diffraction and scattering [73]. These mechanisms will be explained in more detail below:

- Shadowing is a form of attenuation or radio signals due to large obstacles. Even small obstacles such as a wall, a vehicle, or a tree in an alley may block the signal.
- Reflection is the effect of reflected signal in case a radio signals encounters a large object such as a building, mountain or the surface of the earth. The reflected signal is not as strong as the original, as object can absorb some of the signal's power.

- Refraction is the term for the wave propagation effect which occurs when a radio wave propagates from one medium into another.
  A commonly used propagation model for predicting the large scale signal strength is the two-way ground model which considers both a single direct path and a ground reflected propagation path between transmitter and receiver.
- Diffraction occurs whenever there is an obstacle with sharp edges between the transmitter and receiver. The principle of Huygen states that all points on a wavefront can be considered as point sources for the production of secondary wavelets. The secondary wavelets resulting from the obstructing surface of the obstacle gives rise to a bending of waves into the shadowed region of the obstacle. Diffraction allows radio signals to propagate around the curved surface of the earth.
- Scattering is the effect which occurs when there are obstacles between the transmitter and receiver with dimensions that are small compared to the wavelength. The roughness of surfaces induces reflected energy that is diffused in all directions, causing a stronger actual received signal in contrast to predicting the received signal with only reflection and diffraction modes alone.

Fading and multipath

The LOS signal together with the previously described propagation effects lead to the most severe radio channel impairments, known as multipath propagation. Due to the finite speed of light, signals travelling along different paths with different lengths arrive at the receiver at different times. This effect, caused by multipath propagation, is called delay spread. While this effect already occur in the case of fixed nodes, the situation is even worse if nodes can be mobile. Then the channel characteristics change over time, and the paths a signal can travel along vary. This constantly variation in received power is known as short-term fading. On the contrary, long-term fading concerns the variation in received power over over time. In the context of VANETs, variations in signal strength due to small-scale fading are minor when compared to those due to obstacles and are, thus, not explicitly modeled [72].

2.5.2 Vehicular propagation models

The radio channel propagation highly influences the performance and operation of wireless communication systems. The influence can be even more remarkable in vehicular communication networks given the low antenna heights and the highly dynamic network topology. Despite the expected impact of radio channel on the performance and operation of VANET systems, many VANET related studies significantly simplify the radio channel modelling. The study [46] extensively proved that in-accurate, and under certain conditions even wrong, conclusions about the performance and operation of vehicular communication protocols can be obtained when not adequately modelling the radio propagation conditions. This is particularly the case when considering road safety applications with strong reliability and low latency instantaneous communication requirements.
The network simulator ns-3 offers some build in radio propagation models to estimate the wireless signal strength over time and distance. All of these propagation models assume a flat surface, where the simulation environment contains no objects that could block the signal. Some of the build in propagation models are: the Free Space model, the Two-Ray Ground model [73], the Log Distance model, the Nakagami model [71] and the Ricean and Rayleigh fading models [67].
Realistic simulating, especially in the case of an environment with many obstacles (e.g. an urban environment), can only be achieved with propagation models that take the existence of radio obstacles into account. While more realistic, such approaches are prohibitively expensive in terms of simulation computation and clearly infeasible for experimentation with large scale scenarios.

In this section, we explained how the VANET communication channel is modelled and explained the effects of radio wave propagation. Furthermore, we described the modelling of the vehicular channel.

2.6 Summary

Throughout this chapter we explained the concepts of VANETs. First we started with a general introduction of ITS. We showed that a VANET is an instantiation of ITS with its own characteristics of the wireless communication. Then we provided insights in the dissemination of VANET data by showing the recurring communication patterns. In addition we explained that every VANET application is characterized by a ZOI, an application trigger condition and a reception pattern.
Thirdly, we described the WLAN amendment IEEE 802.11p, which is gaining high popularity as the standard for wireless communication in the vehicular environment.
We explained that simulation is intuitive method to perform large scale tests in the field of VANETs. The iTETRIS simulator, which is basically an integration of the traffic simulator SUMO and the network simulator ns-3, offers a platform for realistic, large scale VANET simulations. Finally, we described the wireless channel characteristics in a vehicular environment.

We use this background knowledge to describe the CTLA application in the next chapter, and to design its dissemination protocols in chapter 4. Chapter 5 comprises a large scale simulation study of the CTLA conducted by the iTETRIS simulator.

Chapter 3

The Cooperative Traffic Light Assistant

This chapter includes a specification of the Cooperative Traffic Light Assistant (CTLA), a cooperative traffic efficiency application based on V2I communication. We have designed the CTLA application based on several related studies and standards.
The first section describes the background information of related work. Section 3.2 describes how we are going to use our CTLA application. Then, section 3.3 describes the CTLA application into more detail. The last section 3.4 provides an list of requirements and assumptions.

3.1 Background

During the last decades efforts have been made to create intelligent Traffic Light Controllers (TLC) that can optimize the ever increasing traffic flow. Most of the current TLCs rely on fixed timing plans pre-generated by traffic engineers using optimized models. More sophisticated adaptive TLCs use data from sensors, cameras and inductive loops as input to generate real-time timing plans. For the configuration of real-time adaptive TLCs several goals can be taken into consideration such as: minimizing the average delay of vehicles approaching an intersection, increasing progression by coordinating vehicle platoons between intersections, reducing the queue length of all approaches to an intersection and even reducing overall fuel consumption and pollutant emissions [15].
With the recent cooperative technology developments described in section 2.1 measuring the presence of vehicles shifts from traditional wired infrastructure sensors (e.g. cameras, inductive loops) to vehicle sensors, in which the latter send their information over the wireless medium. Because of the shift in data exchange, not only adaptive TLCs can be provided with extended vehicle information (e.g. vehicle position and speed) for signal processing, but vehicles can be informed individually about the traffic state and traffic light schedule as well. Besides this enhancement of information exchange, the economical advantage of not having to install wired sensors could reduce implementation and maintenance costs.
Due to its promising benefits, the ITS research community started to develop prototypes of several TLC based cooperative applications. An instance of such an application is the cooperative speed advice application.

The cooperative speed advice application along with many other novel cooperative applications was first introduced by the European sponsored FP6 IP Project CVIS [6]. Within the CVIS project, the CURB workgroup developed several intersection control and urban traffic state related efficiency applications like the green route request application and the green wave application. The green wave application was deployed in several vehicle's OBU and on different RSUs which where connected to a TLC using IEEE 802.11a as the wireless technology.
Like the CVIS project, the INNOCAR project developed a traffic light assistant which used the IEEE 802.11a technology and showed the feasibility of the application during several field tests [51].

Several studies assessed the performance impacts of the speed advice application from an application point of view, whereas some of these studies slightly investigated the wireless communication aspects between the TLC and vehicle. In [77] the writers simulated the cooperative speed advice application using a TLC with fixed planning in a microscopic traffic simulator on a large scale basis to estimate the overall fuel consumption and emission. Gear choice and the distance from the traffic light at which vehicles are informed where identified as the key influencing factors on fuel consumption and emissions. In another study [47] an adaptive TLC with a simple scheduling algorithm based on V2I and I2V communication has been simulated. With some small scale simulations the authors demonstrated in terms of traffic fluency the advantages of cooperative adaptive TLC in contrast to the conservative TLC systems. A more advanced scheduling algorithm based on received CAM messages was proposed by [78].

3.2 Use case description

Based on the previous section 3.1 we define the CTLA as an extended version of the speed advice application, that is the CTLA application can not only advice drivers to adjust their speed (as previously described), but drivers can also be informed about the traffic light planning. As an introduction, this section describes the use case.

It is assumed that vehicles approach intersections while beaconing their vehicle data like vehicle type, speed, position and direction located as part of the vehicle's CAM. This CAM message is used by a vehicle to inform the RSU that it is running the CTLA application, i.e., the advertisement of the CTLA service. As will be explained in the next chapter, this advertisement (as part of the CAM) can also be exchanged the other way around, thus from RSU to vehicle.
A RSU near an intersection is connected to the TLC and therefore able to send the traffic light related data to approaching vehicles. Depending on the type of implementation, this data could be the traffic light schedule (i.e. schedule for red, yellow and green phases) or an actual speed advice which will be designated to every vehicle. A vehicle equipped with both an OBU and the traffic light assistant application is able to receive and process the information. After the calculation of a speed advice, the speed can be adjusted in an automated way by the vehicle's cruise control, or manually presented to the driver of the vehicle by means of a visual HMI. Consequently the chance of arriving at the intersection while the traffic light of the vehicle's lane is green is increased. A schematic overview of the application is depicted in the figure below.

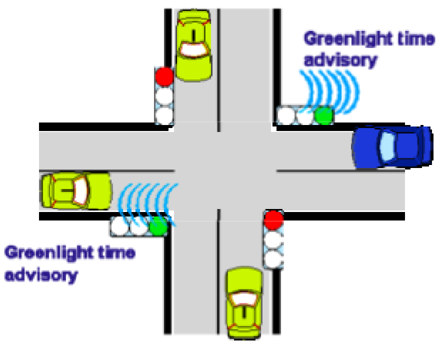


Figure 3.1: Cooperative traffic light assistant overview [42]

3.3 Application description

Before the deployment of a CTLA application, traffic engineers try the find the optimal configuration setting that meets the preferred policy of the road side scenario. For example, one of the stakeholders (e.g. the government) can demand a priority of vehicles driving on a main road crossing one or more intersections controlled by traffic lights. Obviously the configuration of the TLC, or even an cascade of TLCs, depends on the type of policy. Listing all these policies falls more into the area of traffic engineering, therefore we try to describe the application independently of the policy.

TLC algorithms can be classified as adaptive and non-adaptive. Adaptive TLCs change their scheduling strategy continuously, non-adaptive TLCs execute a static planning as a cycle. The cycle time of none-adaptive TLCs is a predefined setting and mostly based on historical traffic data measured near the location of the intersection [47].
Because of the cyclic character of a non-adaptive TLC, vehicles interested in the traffic light phase of a non-adaptive TLC only have to receive the information once. An adaptive TLC on the other hand requires periodical update since the traffic light cycle depends on the configured traffic policy and the actual traffic near the intersection [47].

An advanced speed-advice algorithm could consider many factors such as the intersection's queues length, expected traffic flow, the scheduling of subsequent traffic lights and many more. Though the existence of an accurate speed-advice algorithm is a key issue in the application assessment of such a CTLA. In this study the focus is not on improving speed-advice algorithms, but on an in-depth analysis of the wireless communication impact. Therefore, we have created a basic algorithm that considers a small set of variables that is sufficient enough to calculate the speed advice. Nevertheless a chance exists that a vehicle faces a red light upon its arrival at the intersection. This will be explained in more detail later this chapter.

The basic algorithm in this study calculates the speed advice based on two variables: (1) the position of an approaching vehicle and (2) the traffic light planning. Figure 3.2 depicts a schematic overview of the scenario where a vehicle approaches a traffic light controlled intersection. The distance from the vehicle at time $t = t_0$ to the intersection is denoted as L. A TLC runs cycles which includes a *red-orange-green* switching pattern per cycle. The actual time of one cycle depends on the TLC type: a non-adaptive TLC includes a fixed cycle length in which the duration of the red and green light might differ, adaptive TCL types are characterized by dynamic cycle lengths. For simplicity, our experiments described in chapter 5 use fixed cycle lengths.

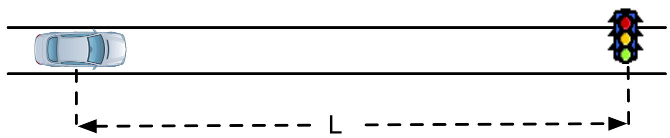


Figure 3.2: A vehicle approaching a traffic light at speed v. Based on the distance L and the traffic light planning tr and tg, a speed advice can be calculated

At time $t = t_{gi}$ the traffic light will switch to green and at time $t = t_{ri}$ the traffic light will switch to red. The i denotes the i^{th} cycle number of the traffic light planning over time.
Assuming an initial red state so that $t_{r0} < t_{g0}$, the speed advice is calculated as follows:

1. Given the maximum allowed speed of the road v_{max} and distance L, if the vehicle travels as maximum speed, it will arrive the intersection at time $t_{max} = L \ / \ v_{max}$
2. If the vehicle faces a *green* light at arrival time t_m (that is - for certain cycle i - it holds that $t_{gi} < t_{max} < t_r i$), the speed advice (v_a) will be to drive at maximum speed: $v_a = v_{max}$
3. If the vehicle faces a *red* light at arrival time t_{max}, the next green time t_{gi+1} is used to calculate the speed advice (v_a) according to the formula: $v_a = L \ / \ t_{gi+1}$
   However, a vehicle is not allowed to drive slower than a minimum speed v_{min} so the speed advice $v_a > v_{min}$. The reason of v_{min} is to avoid the vehicle to be running a ridiculously low speed that might cause dangerous situations on the road. Therefore, if the calculated v_a is smaller than v_{min}, the driver is notified that no speed is advised since it is inevitably to encounter a red light at this intersection.

4. If the vehicle passes the intersection, it will reject any speed advice.

We would like to emphasize that our basic algorithm is far from ideal since several variables are ignored (e.g., queues, the time it takes for a vehicle to accelerate or decelerate to adjust its current speed, the traffic light planning of the next intersection, etc). It is expected that - especially in the case of scenarios with a large vehicle densities - vehicles using this algorithm will not always encounter a green light phase, we think the formula is sufficient to change the mobility pattern of approaching vehicles.

A RSU is responsible for the communication of the application related traffic light data. In order to establish a connection between vehicle and RSU, both nodes should run an instance of the CTLA with the same underlying communication stack.

3.4 Requirements

Based on several field tests of large European projects, the standardization organisation ETSI defined a set of requirements for the *greenlight optimal speed advisory* use case [42]. The requirements assume a implementation of the application where the RSU broadcasts the traffic light schedule with a frequency of 2 Hz to approaching vehicles. Furthermore all vehicles within transmission range should be informed with a maximum latency time of 100 ms. The transmission range, however, is not specified in [42]. Although at first sight these requirements perhaps look like a well established list, the list of application and system requirements is rather short and the specified communication requirements are irrelevant or incorrect. In the next sections we try to refine the list of requirements by listing the application, communication and performance requirements. Furthermore, in order to have a complete list of requirements we add several assumptions.

3.4.1 Communication requirements

The communication requirements are derived from the previously described requirements. Additionally every station is equipped with a beaconing application (as described in section 2.2), since it is likely that this will be the case for real cooperative ITS scenarios. The CAM message size includes all the required data and the overhead created by security additions. The beacon rate of the CAM message is set to a frequency which still can be seen as a reasonable beacon rate for common awareness. The following communication requirements can be distinguished:

- ITS-G5A multi hop radio communication coverage in the 5,9 GHz band [43]
- The system should use the minimum load on the medium without harming the other requirements
- The transmission power ranges from -85 dBm [37] to 33 dBm EIRP [43]

3.4.2 Performance requirements

During this research we are mainly interested in the scalability of the system. Scalability is defined as the ability to handle the addition of nodes or objects without suffering noticeable loss in performance or increase in administrative complexity [61]. Referring to the motivation of this research described in the introduction, a large node density is very likely in the case of urban environments during daily peak times. To challenge the total system we state the following performance requirements:

- The application should be used by the maximum number of vehicles without experiencing significant loss in performance
- Within the ZOI, a vehicle should be travelling as much as possible with the most up to date application data

- The application should be usable in every kind of vehicular environment, e.g. urban, sub-urban, highway

3.4.3 Assumptions

All of the aforementioned requirements are based on standardization efforts or on the results of projects with a similar application. However, there are still several assumptions to be made in order to complete the list of requirements. Most of these requirements fall within the area of traffic engineering, and since - to the best of our knowledge - this kind of application is relatively new in this area, literature about this topic does not exists. Therefore we make some assumptions to complete our requirements list.

The correct timing of displaying the application information to the driver depends on the geographic location of the vehicle relative to the intersection. Pinpointing the geographic area includes targeting the roads as well defining the minimum and maximum distance to the intersection. Determining this ZOI should be aligned with the traffic objectives as mentioned in the introduction of this chapter, and is more devoted to the area of traffic engineering. Nevertheless, the expressed ZOI could have a major impact on the communication requirements. For example, in case the defined geographic area exceeds the transmission range of the RSU the communication architecture should include multi-hop technology. In the list of standardized applications and requirements in [42] nothing is mentioned about the geographic location at which vehicles should be informed. In [51] the writers claim the longer the distance between the traffic light and the vehicle is, the more efficient their application will be. However they use a information range of 500 m in their field tests, which happens to be exactly the transmission range of their used wireless technology. In [77] it is claimed that there exists some point at a distance around 1000 m away from the intersection, that a speed adjustment is not of influence on the emission any more. Although the writers argue that such a point exists and do not provide an exact distance, we adopt the information range under the assumption that this is the saturation point. For the minimum distance we adopt the assumption of [77] which states a driver decides to slow down to zero if it approaches a red light and no communication is used at close to 100 m.
By now we can add the following assumptions to the list of requirements:

- All vehicles on the roads directly connected to the intersection should be informed
- The minimum information distance is 100 m
- The maximum information distance is 1000 m

The art of realistic modelling how drivers approach a traffic light controlled intersection falls in the area of traffic engineering. In this research, the focus is not on newly optimizing traffic-light approaching behaviour, but on an in-depth analysis of the communication modes and on the performance's impact in large scale scenarios. For simplicity we assume that if a vehicles receives a speed limit notification, it will adopt this advice immediately.

- If a vehicle receives a CTLA application message (containing the traffic light planning or a new speed advice), and the vehicle belongs to the ZOI, it will immediately adopt its speed according to the calculated speed advice

Finally, we add several assumptions to the list of communication requirements:

- Every vehicle is equipped with an OBU which runs an instance of the CTLA application
- Every intersection contains one RSU which is responsible for the communication of the application data related to the corresponding intersection
- On the forehand, vehicles are not aware of the RSUs and thus have to be notified about their presence and services
- Every vehicle and RSU only communicates beacon CAMs and CTLA messages
- Both the beacon service and CTLA application use the ITG-G5A CCH channel for wireless communication

- By default every vehicle and RSU beacons a CAM packet of 500 bytes [37] at a frequency of 1 Hz
- Every node includes a CALM architecture (see section 2.1.2) with geo-addressing support (see section 2.2.3)

3.5 Summary

In this chapter we specified our CTLA application and explained the main mode of operation of this application. We mentioned that such a traffic efficiency application could result in a number of efficiencies ranging from minimizing the average delay of vehicles approaching to overall full consumption reduction. We have defined a list of requirements based on standardization efforts, several projects and our own assumptions.

In the next chapter we will design several dissemination protocols to transfer the CTLA data from RSU to vehicle. Based on the requirements of section 3.4 we will evaluate these dissemination protocols in chapter 5.

Chapter 4

Application data dissemination protocols

Having described the general operation and the requirements of the CTLA application in the previous chapter, the question remains of how to disseminate the application data? As we will explain, the application could be disseminates in several ways, in this chapter we will introduce three of our own dissemination protocols that can function as a dissemination protocol for the CTLA application.
As already has been shown in [30] designing an ITS application involves several design choices, especially on the communication aspects of the system. In terms of the OSI layer-model, the dissemination protocols described in this chapter are part of the application layer. The network attributes which we will include in this chapter's discussion, are more or less determined by these dissemination protocols.

4.1 Overview

In the first chapter we introduced the term ZOI, which defines the main geographical area of interest, i.e. the vehicles which should receive an application message. As defined in the requirements section 3.4, this area includes all the approaching vehicles within a range of 1000 m from the RSU.

The responsibility of speed calculation can be granted to the vehicle or to the RSU. Each option contains its own variants of data exchange between vehicle and RSU:

- The speed advice calculation is the responsibility of the *application running on the RSU* - in this way the RSU is in total control of the speed advice calculation and dissemination. The RSU is directly connected to the TLC and uses the deployed speed advice algorithm to calculate a speed advice for each individual vehicle. The static road maps of the roads within the ZOI are known available to the RSU's algorithm and can be used for calculation of the speed advices. However, with this option it is required that the vehicle informs the RSU about its location, before the RSU start the speed advice calculation.
- The speed advice calculation is the responsibility of the *application running on the OB*U of the vehicle - with this option a traffic light planning is send from the RSU to the vehicle. Upon reception of the traffic light planning a speed advice can be calculated by the CTLA algorithm deployed on the vehicle's OBU.

Each option comes with its own dissemination protocol and routing protocol. Throughout the next sections, we identify the various dissemination protocols by pointing out two application characteristics: (1) the application trigger condition, that specifies how the application is triggered which is generally either periodic, event- driven, or user-initiated and (2) the recipient pattern of application messages, that specifies the pattern of potential message recipients for an event. For each dissemination protocol we illustrate the data exchange pattern and provide a description of the network characteristics.
In section 2.2 we listed the most commonly used dissemination modes in local ad-hoc communication

systems. There we discussed several application characteristics that are of relevance to application dissemination design, including the concepts of reception pattern and application trigger condition. The reception pattern of application messages specifies the pattern of potential message recipients for an event. These reception patterns will be used to construct the dissemination protocols in the next sections.

4.2 One-to-one dissemination with RSU-CAM trigger

In the case of the first application implementation, in which the RSU is in charge of the speed computation, a speed advice is calculated for each unique vehicle. This implies that the RSU should send a personalized message to each individual vehicle. Since we defined the concept of ZOI, vehicles outside this area should dismiss received packets.

In this case, the RSU sends a message to an individual vehicle, which implies *one-to-one pattern*. As mentioned previously, the choice of reception patterns determine more or less the routing protocol. Section 2.2 relates the one-to-one reception pattern to unicast routing. Thus, the routing protocol used in this scenario should support unicast routing.
Second, there should be some trigger condition to activate the application. In a realistic scenario, it is likely that an arriving vehicle is not aware of the RSU and its deployed applications. Therefore if a vehicle enters the aforementioned ZOI, it is triggered by the reception of a RSU's service advertisement message. As described in section 2.1.2, the service advertisement mechanism - standardized by CEN DSRC and IEEE WAVE - uses a period beacon scheme (e.g., as part of the CAM) to inform other stations about the service provider's running services. It should be noted that our choice to use the CAM to adverse the service restricts the ZOI to the transmission range of the RSU. The reception of advertisement enables the vehicle to recognize the type service type, which triggers the CTLA application deployed on the OBU to initiate a peer-to-peer speed advice request. Figure 4.1 depicts the message exchange between vehicle and RSU for the unicast communication pattern.

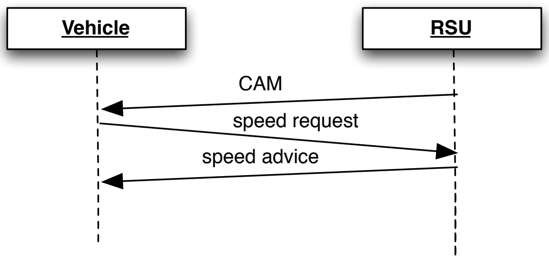


Figure 4.1: One-to-one dissemination triggered by the RSU's CAM

4.2.1 Network characteristics

The identified one-to-one pattern requires unicast routing protocol, which requires in general (1) the knowledge of node locations (by means of an addressing format), and (2) a method of forwarding packets toward their destination. Section 2.2.3 illustrated the notion of geographical addressing, an addressing scheme that uses the node's geographic position as the addressing format in the routing location table. Many studies assessed the performance of forwarding algorithms (e.g. [38, 54, 59, 60]). We try to keep our focus on data dissemination protocols, rather the finding an optimal forwarding protocol. Nevertheless, to support some basic forwarding functionality, a basic geo-networking protocol is used. This basic geo-networking protocol is founded by the GeoNet project [45] and uses a sender-based forwarding mechanism. Sending-based forwarding schemes use a sending node to select the forwarding node to further forward the packet. Contrarily, receiver-based forwarding schemes grant the responsibility of the forwarding decision to the receiving node [54].

The basic geo-unicast forwarding mechanism is relatively simple: a sending node calculates the node closest to the destination node and subsequently sends an unicast message to this closest node. This mechanism repeats itself until the destination is reached. For the distance calculation between two nodes, the latitude/longitude value pairs of any two nodes are taken, and converted into a distance-value expressed in meters. Each nodes maintains a location table, holding a list of its neighbouring nodes. The forwarding algorithm of the sender operates as follows:

1. a node S generates a geo-unicast packet P with destination address D. The destination address is extracted from previously received message (as can be seen in figure 4.1 this previous message can be the CAM or the speed request);
2. if there is a fresh entry in location table which says that D is a direct neighbour, then send P to D (D should be within the communication range);
3. else, if the position of D is already provided by the upper layer or known from the location management table, then D-location = geographical location of D;
4. else, ask the location service to provide the geo-location of D (D-location = geographical location of D);
5. else if there are neighbours available around, then for each neighbour i, calculate Dist(i, D) which corresponds to the distance from the location of i to the location of D and send P to the neighbour i which has the shortest Dist(i, D);
6. else, put P in the store and forward buffer (i.e., postpone the sending until a suitable forwarding candidate appears).

For each receiving node j, the following steps are executed:

1. node j receives a Geo-unicast packet P to be delivered to D;
2. j updates the location table by updating/adding the two entries that respectively correspond to the node that generated the packet P, and the node from which the packet has been received;
3. if j is the destination D, then send payload to upper layer;
4. else, if there is a fresh entry in location table which says that D is a direct neighbour, then send P to D (D should be within the communication range);
5. else, if there are neighbours available around, then for each neighbour i, calculate Dist(i, D) which corresponds to the distance from the location of i to the location of D and send P to the neighbour i which has the shortest Dist(i, D);
6. else, put P in the store and forward buffer.

4.3 One-to-one dissemination with vehicle-CAM trigger

The second dissemination protocol is more or less a derivation of the previous protocol described in section 4.2. It uses the same reception pattern, but differs at the trigger condition.
With the previous protocol the CTLA application running on the vehicle's OBU is triggered by the reception of a RSU's CAM message. The trigger condition of this protocol is the other way around, i.e. the RSU's application instance is trigged upon the reception of a vehicle's CAM message. Hence the number of exchanges messages per cycle is reduced from three to two. The figure below shows the exchange pattern between vehicle and RSU.

As with the previous protocol, the ZOI is restricted to the transmission range of the RSU's service advertisement message (i.e., the CAM). The routing protocol used in this dissemination protocol is similar to the described previously geo-unicast protocol.

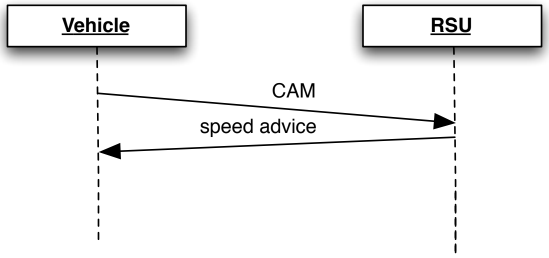


Figure 4.2: One-to-one dissemination triggered by the vehicle's CAM

4.4 One-to-zone dissemination

While the previous protocols described in section 4.3 and 4.4 do not disseminate any road or TLC related data, the protocol described in this section disseminates the traffic light planning to all the vehicles within the ZOI. The traffic light planning concerns a specific group of roads which implies - according to section 2.2 - an one-to-zone reception pattern. This can be categorized to the geo-broadcast communication pattern which is explained in section 2.2. The geo-broadcast communication pattern requires a geo-broadcast routing protocol at the network layer.
In contrast to the previously described dissemination protocols, the exchange pattern between vehicle and RSU in this implementation is relatively simple: the RSU sends a periodic general message to all the vehicles within the ZOI. Figure 4.3 depicts the message exchange pattern for this dissemination mode.

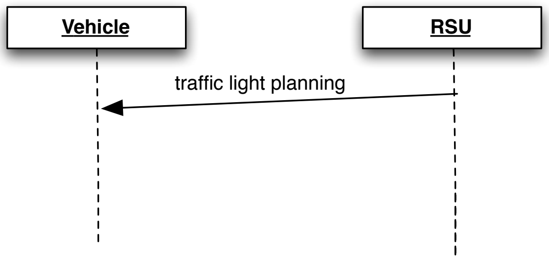


Figure 4.3: Broadcast communication pattern

For understandability, we omitted the CAM message exchange in figure 4.3 since it is not used by the CTLA application in case of this protocol (however, both nodes exchange CAMs actually).

The payload of the message containing the traffic light planning in figure 4.3, is constructed according to the xml message format of the CVIS project's *Speed profile application* [35]. The CVIS project developed a prototype of the Speed profile application which is similar to our CTLA application. The CVIS Speed profile application is using the broadcast method to inform vehicles about the traffic light planning of a cascade of intersections. Each RSU provides approaching vehicles with the following information:

- Min-max speed limits, which include max. upper and min. lower speed limits
- For each intersection, time to next green
- Time of generation of the information
- Spatial validity
- Time validity
- Reference corridor description

The reference corridor description is built up of directed segments of roads, expressed as geographical references. The periodic broadcast message contains the information of every lane. Based on the fields listed in [35] we use a total payload size of 10 Kb.

4.4.1 Network characteristics

The identified one-to-zone pattern requires a geo-broadcast routing protocol. GeoNet's geo-broadcast protocol [45] describes a forwarding mechanism that uses geo-unicast to forward the geo-broadcast packet to the ZOI, in case the sending node does not belong to the ZOI. For all the scenarios we will use in order to challenge the CTLA application, it holds that the sending node (i.e., the RSU) is part of the ZOI. Thus none of these scenarios employ geo-unicast to forward geo-broadcast packets. Furthermore GeoNet's basic geo-broadcast protocol does not include an advanced flooding mechanism; every node that belongs to the broadcast geo-area rebroadcasts a received packet with probability 1. Though to avoid the possibility of a *broadcast storm* (a scenario in which there is a high level of contention and collisions at the link layer due to an excessive number of broadcast packets), we use a more advanced broadcast forwarding mechanism.

In [86], the writers proposed several advanced broadcast forwarding mechanisms that can avoid the broadcast storm effect. The basic broadcast techniques follow either a *1-persistence* or *p-persistence* rule: a packet if forwarded with probability *1* or probability p respectively. Though the writers described several forwarding mechanisms, we choose the mechanism that provided the greatest reduction in broadcast redundancy while still offering acceptable end- to-end delay and reachability. It was found that *slotted 1-persistence* provided the fastest dissemination [86].
The *slotted 1-persistence* [86] mechanism operates as follows:

1. a node S generates a geo-broadcast packet P with destination area D;
2. upon receiving a packet from node i (which could be node S), node j checks the packet P and rebroadcasts with probability *1* at the assigned time slot $T_s ij$, if it receives the packet for the first time and has not received any duplicate packets before its assigned time slot, otherwise, it discards the packet.

Denoting the relative distance between nodes i and j by D_{ij} and the average transmission range by R, and the predetermined number of slots N_s (set to 5 [86]), T_{sij} can be calculated as:

$$T_{sij} = \tau \times N_s \left(1 - \left[\frac{min(D_{ij}, R)}{R} \right] \right) \tag{4.1}$$

where τ is the estimated one-hop delay, which includes the medium access delay and propagation delay, in [86] defined as 5 ms.
The result of using formula 4.1 is that the nodes for which D_{ij} (i.e., the largest distance to the sender) is larger, will use an lower timeslot number, which implies lower waiting time to forward the packet. However, this will only be done if no other node rebroadcasts in the mean time.

This slotted 1-persistence flooding scheme described above breaks the synchronisation of simple flooding, which would otherwise result in all nodes trying to access the medium simultaneously. It is identified by [80], however, that a similar synchronisation can occur within one slot when vehicle densities are high (as is very likely in congested traffic conditions). As such, this slotted 1-persistence flooding does not completely solve the broadcast storm.
As a solution, we adopt the *micro-slotted-1-persistence* introduced by [80]. In essence, this scheme is a slotting scheme at a fine granularity and uses a similar function as equation 4.1 to calculate as small extra delay which is added to every delay T_{sij} within one slot:

$$T_{ms_{ij}} = \tau_{ms} \times N_{ms} \left(1 - \left[\frac{D_{ij} mod S}{S} \right] \right) \tag{4.2}$$

where τ_{ms} is the duration of a micro-slot, taken as the time of one DIFS (64 [50]), S is the size of a slot defined as $\frac{R}{N_s}$, and N_{ms} is the number of micro-slots per slot based on the estimated transmission range

R, number of slots N_s and average vehicle length l:

$$N_{ms} = \frac{\frac{R}{N_s}}{l} \quad (4.3)$$

As a result, the total wait time for node i after receiving a packet from node j is the sum of 4.2 and 4.3:

$$T_{wait} = T_{s_{ij}} + T_{ms_{ij}} \quad (4.4)$$

Figure 4.4 shows an example of the slotted-1-persistence mechanism with τ set to 4 (i.e., 4 chunks) whereas a shorter waiting time will be assigned to the nodes located in the farthest chunk. Thus, the original accident message sent by the first vehicle (on the right) will be immediately forwarded by the vehicles in chunk $T = 0$. If vehicles in the lower chunk $T = 0$ will not receive this forwarded message, they forward the message after passing τ time. This process will repeats itself for every chunk

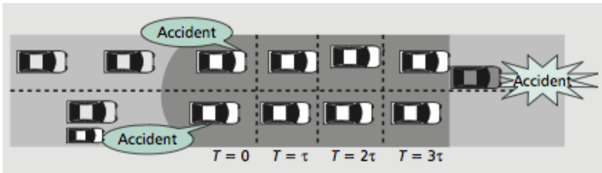


Figure 4.4: Example of the slotted-1-persistence mechanism (copied from[86])

4.5 Summary

In this chapter, we showed that the CTLA application could be differently implemented based on the responsibility of the speed advice calculation. We discussed three data dissemination protocols which differentiate by the application trigger condition and reception pattern. For each protocol, we described the application and network characteristics of the data exchange pattern. We showed that many of the network attributes are closely related to specific application characteristics, e.g. a one-to-one pattern implicitly requires an unicast routing protocol.
In the next chapter, we evaluate the performance of these three dissemination protocols for different kind of scenarios.

Chapter 5

Performance evaluation

The Cooperative Traffic Light Assistant application described in chapters 3 and 4 has been implemented in the iTETRIS simulator (for a description of the iTETRIS simulator we refer to section 2.4.2). In order to evaluate the performance of the application in large scale scenarios, several experiments have been conducted which are described in this chapter.
With a system as complex as VANETs, several factors might influence the system performance differently in large scale operations. Therefore we start this chapter with an identification of the key influencing factors.
Section 5.2 explains the performance metrics used in our simulations to compare the results. In the subsequent section 5.3 we describe the general simulation set up and introduce three different scenarios which have been used for out experiments.
The results of these experiments, conducted by the VANET simulator iTETRIS, are described in section 5.4. We end this chapter with a discussion of the results.

5.1 Factors influencing the performance

In this section, the influencing factors that determine the overall system performance are analysed. In order to study the performance of a specific system, the key influencing factors of the system should be extracted and mapped to the performance metrics.
Although medium access layer parameters, e.g. the backoff window size, frame length, as well as physical layer parameters affect the performance of V2X communication [36], this research keeps a strict focus on the dissemination modes. Most of these parameters are chosen according to the expertise of related studies. For simplicity, no priority on the MAC layer is used.
In the following, we identify the key influencing factors of the performance of the system.

5.1.1 Mobility and vehicle density

It is widely believed that the number of vehicles is one of the most important influencing factor in the performance of a cooperative system. Especially during peak times the number can grow, but in the end the total number of vehicles is limited to the capacity of the road segment.

The vehicle density is measured as the number of vehicles per km road. The vehicle densities illustrated in the results of the simulation experiments described in section 5.4 have been measured as the average number of vehicles per km road during the whole simulation time.
Depending on the type TLC algorithm, we expect a couple of mobility patterns each characterized by a different vehicle density spread. It is expected that the variations in mobility according to the distance to

the RSU, will influence the performance differently. This motivates our decision to relate the performance metrics of the next section to the distance of the RSU.

5.1.2 Radio obstacles

The relatively low heights of the vehicle's antennas imply that the optical Line-Of-Sight (LOS) can easily be blocked by an obstruction, either static (e.g., buildings, hills, foliage) or mobile (other vehicles on the road). There exists a wide variety of experimental studies (e.g., [70, 72, 34]) dealing with the propagation aspects of V2V and V2I communication in which obstacles have been identified as the key factors affecting the signal propagation.
As discussed in section 2.5 radio signals are subject to large-scale fading and small-scale fading. The effect of large-scale fading on the signal varies depending on the environment (e.g. open field, urban, sub-urban), and especially between LOS and non-LOS communication in the same environment. Compared to the LOS path, a non-LOS has lower signal strength because the signal travels a longer distance than the direct path and is attenuated. In addition, if obstacles are closer to the road, as in urban environments, the attenuation on the signal will even increase more. For instance, the non-LOS transmission range for two vehicles communicating around the corner of a block in an urban setting can be 40% shorter than that in a sub-urban setting [72].
Besides the recognition of static obstacles as key influencing factors, it is likely that mobile obstacles (i.e. the vehicles) will often obstruct the LOS. In [70] it is pointed out that vehicles blocking the LOS significantly attenuate the signal when compared to LOS conditions across all environments. Measurements showed that the additional attenuation decreases the packet delivery ratio at longer distances, halving the effective communication range for target average packet delivery ratios between 90% and 50%. The writers of these studies argue that realistic modelling, especially in the case of an urban environment, can only be achieved with propagation models that take the existence of radio obstacles into account. While more realistic, such approaches are prohibitively expensive in terms of simulation computation and clearly infeasible for experimentation with large scale scenarios. Secondly, at time of writing, the lack of requisite supporting functionality in the simulator [11] makes it a great challenge to deploy such kind of scenarios.
In order to simulate the existence of obstacles across all environments despite all these problems, we adjust the transmission power over a series of experiments in align with the environment. The findings of [72],[70] justifies our decision to vary the transmission range. Using this approach has the additional advantage that we generate results for a wide variety of transmission ranges: although maximum transmission power is restricted by governmental rules [43], the preferred transmission range is not standardized nor agreed by the community at time of writing.

5.1.3 Road topology

Most performance studies differentiate between the road topology based on the environment (e.g. high way, urban, sub-urban). Instead of defining these specific scenarios, we decompose the road scenarios into the basic road elements which consists of road segments, intersections and speed limits, and variate over these elements during our experiments. For example, the speed limit of a single road segment makes the difference between a high way (i.e., higher speed limit) and an urban road (i.e., lower speed limit). Further, we reduce our research on different environments with multiple intersections to the case of two adjacent intersections with overlapping ZOIs. The objective of this scenario is to quantify the effect of the overlapping ZOIs on the system's performance.
In section 5.3 of this chapter three scenarios are introduced, each with a different number of roads and intersections. For each scenario, we conduct exactly the same experiments with equally configuration.

5.1.4 Other influences

The communication channel of the vehicular network is scarce and can be used by a wide range of applications [42]. It has already been shown that the beaconing application, described in [32], could be of major impact on the vehicular control channel [36]. As described in section 2.3.2 the European ITS-G5A defines several communication channels, each reserved for their own type of application communication. Without making hard assumptions about the channel load caused by other ITS application, we argue that a dissemination strategy with the minimal bandwidth usage is preferred since this leaves more bandwidth available for other kinds of ITS applications. Thus, in this study, with the exception of the beaconing application, we leave research on the influence of other ITS applications to future work.

5.2 Performance metrics

The effects of using one of the dissemination protocols described in 4 should be investigated on the appropriate level of operation. Most studies in the field of the traffic light related I2V application focus on the environmental impact [77] or the impact on the traffic flow [47]. Mean fuel consumption, mean travel time and mean waiting time performance metrics where used to investigate the efficiency of the implemented algorithms. Throughout all these studies communication aspects where simplified or even treated as being ideal.

As stated in the introduction, this research aims at finding which of the dissemination strategies performs the best for the CTLA application. That is, finding the optimal dissemination protocol based on the application requirements described in section 3.4.
This section briefly describes the key performance metrics, i.e. the performance criteria, which will be used to compare the results of the experiments described in the next chapter.

The rest of this section explains the following performance metrics: notification distance, common channel utilization, delivery ratio and end-to-end delay. It should be noted that only the vehicles within the ZOI are considered as relevant to the application. Measurements outside this zone are not of interest, which constrains the calculation of the metrics to measurements within this geographical zone.

Notification distance - the distance at which - for the first time - a vehicle receives TLC related data from a RSU. As soon as a vehicle receives a CTLA message containing a speed advice (in case of the unicast protocols) or the traffic light planning data (in case of the broadcast protocols), the vehicle measures its distance to the intersection. Obviously, this performance metric is only measured by vehicles and not by RSUs.
In the result analysis of section 5.4, the notification distance is showed as the total number of vehicles - that received its first message - as a function of the distance to the RSU. Measurements at a certain distance are assigned to chunks of 50 m.
This performance metric is measured on the application since only the application layer is able to differentiate between the package contents.

Common channel utilization - the fraction of time that an average node experienced the medium as busy, due to transmission or receiving of CTLA messages or CAMs. This metric is measured by all the vehicles inside the ZOI during the entire simulation time. Common channel utilization can be expressed as the average fraction of time the medium is sensed busy according to the formula:

$$\text{utilization} = \frac{\sum_{i=1}^{n} S_i}{n} \tag{5.1}$$

where S_i equals the total sum of non-idle times (e.g., the node is in transmission or reception mode) of node i, and n equals the total number of nodes.
In contrast to the notification distance metric, which is measured on the application level, this performance metric is measured on the wireless medium (i.e., the common channel) level.

Delivery ratio - the percentage of CTLA messages, that did not reached the vehicle. Depending on the protocol used, the message that is assigned as the send message is:

1. the vehicle's CTLA request message in case of the one-to-one dissemination with RSU CAM trigger (section 4.2)
2. the CTLA message send from the RSU to the vehicle in case of the other two dissemination protocols (section 4.3,4.4)

As with the notification distance metric, this metric is measured on the application level since it can be the sum of the of request-response exchange (in case of the one-to-one dissemination with RSU CAM trigger).
Section 5.4 shows the delivery ratio both as function of vehicle density and as function of the distance to the RSU.

End-to-end delay - depending on the protocol used, the end-to-end delay is defined as:

1. the time from the moment a CTLA message is requested by a vehicle, until the moment a CTLA message is received by the vehicle, in case of the one-to-one dissemination with RSU CAM trigger (section 4.2)
2. the time from the moment a CTLA message is send by the RSU until the moment it is received by a vehicle, in case of the other two dissemination protocols (section 4.3,4.4)

Because this metric is measured on the application level, it includes the medium access delay, as well as transmission and propagation delay for source transmissions and forwarding transmissions.
Section 5.4 shows the end-to-end delay both as function of vehicle density and as function of the distance to the RSU. The average delay for a chunk is calculated as the average delay of messages that has been received by vehicles located in a chunk upon the send time of the message.

5.3 Simulation experiments

The result analysis described in the next section is based on the conduction of a large series simulation experiments. This section describes the simulation set up that has been used during these experiments. First we start with a description of the general set up. This description includes the configurations of three of the iTETRIS blocks (figure 2.15): the application, SUMO and ns-3.
Then, in section 5.3.2 we describe the SUMO scenarios We have defined three scenarios, each with a different road topology that forms the starting point to variate over the other factors of influence: vehicle density, TLC cycle length, and maximum speed. In order to show the performance of the dissemination protocols described in chapter 4, we conducted every scenario three times each with a different configured dissemination protocol.

5.3.1 General setup

In the following we describe the simulation setup and define the notions used in the analysis.

Vehicle mobility/density: Due to variations in driving behaviour (e.g. adoption of the speed advice, overtaking manoeuvres) as well as vehicle queuing caused by red light stops, vehicle density is not equally distributed over the length of a road but varies heavily over time. As stated before, it is known that vehicle density has a major impact on the performance metrics, which encourage our work to quantify the extent of the effect of varying vehicle density on our performance metrics.

Applications: All participating nodes employ both the beacon application and the traffic light assistant application according to the system requirements of section 3.4. The beacon application disseminates the standardized CAM messages including all the node information specified by [39]. The additional expected security overhead expand the total packet size to 500 bytes. Packets are send to all surrounding nodes with a rate of 1 Hz.
The traffic light assistant application deployed on the RSU is directly connected to the TLC. In order

to influence the mobility pattern, we vary the cycle time of the TCL over the experiments. Table 5.1 summarize the application simulation parameters.

Table 5.1 and 5.2 summarizes the application and scenario simulation settings.

Parameter	**Description**	**Value**
Beacon rate	Beacon rate of CAM message of both vehicle and RSU	1 Hz
Beacon message size	Total size of the CAM message including all headers and additional security payload in bytes	500 b
Application message size broadcast protocol	Total size of the broadcast message including all headers and additional security payload in bytes	2000 b
Application message size unicast protocols	Total size of every unicast message including all headers and additional security payload in bytes	300 b
TLC cycle length	Traffic light planning cycle length of the Traffic Light Controller in seconds	90s
Vehicle density	Average number of vehicles per km road	[10-500]
Simulation time	the simulation time for each experiment	300 s

Table 5.1: Application & scenario simulation parameters

Parameter	**Description**	**Value**
Acceleration	The acceleration ability of vehicles	0,8 m/s^2
Deceleration	The deceleration ability of vehicles	4,5 m/s^2
Car following model	SUMO mobility model	Krauß-model
Driver imperfection	The driver imperfection (between 0 and 1)	0,5
Departure lane	The lane on which the vehicle shall be inserted	random
Vehicle length	The vehicle's brutto-length (length + offset to leader while standing still)	5 m
Max speed	The vehicle's maximum velocity in km/h	[50,70]
Min speed	The vehicle's maximum velocity in km/h	30

Table 5.2: Mobility simulation parameters

Communication configuration: Every participating vehicle is equipped with ITS-G5A technology and uses the architecture described in section 2.1.2 as the run-time environment for the applications. The antenna is centrally mounted on the vehicle's roof for best possible reception [58]. All nodes communicate on the ITS-G5A control channel, which is limited to a maximum throughput of 6 Mb/s.
Similarly the RSU is equipped with the same architecture and communication technology. To analyse the impact of obstacles we evaluate different transmission ranges in the range from 300 m to 800 m

We conduct a series of experiments in which we variate the extend of areas with NLOS conditions. Additionally, the vehicle mobility scenarios of the first experiments are used to the increase the vehicle density.
The communication simulation parameters are summarized in table 5.3 and 5.3.

Parameter	**Description**	**Value**
CWmin	Minimum Contention Window size	15
CWmax	Maximum Contention Window size	1023
AIFSN	Arbitrary Inter Frame Space Number	9
Slot time	Slot time	16 μs
SIFS	Short Inter Frace Space	32 μs
RTS/CTS threshold	Threshold to use the RTS/CTS mechanism	3000 b
Fragmentation threshold	Fragmentation size	2300 b
Max retry limit RTS	The maximum number of retransmission attempts for an RTS	7
Max retry limit data	The maximum number of retransmission attempts for a DATA packet	7

Table 5.3: MAC layer simulation parameters

Parameter	**Description**	**Value**
Radio channel	ITS radio channel	ITS-G5A CCH 5,9 GHz
Radio interface	Wireless communication technology	ITS-G5A
Radio propagation model		Log distance loss model
Reference loss parameter		41.8588
Paths loss exponent	Paths loss exponent for different environments	3
Tx range vehicle	Maximum transmission range in m	[300,900]
Tx range RSU	Maximum transmission range in m	[300,900]
Data rates	Maximum throughput	6 Mb/s

Table 5.4: PHY layer simulation parameters

5.3.2 Scenarios

The scenarios described in this section can be distinguished by their road topology and the number of RSUs. Each scenario has been created in SUMO and served as a starting point for the experiments. For each experiment we configured the iTETRIS simulator with the scenario and the general settings of the previous section and measured the performance metrics described section 5.2.

Scenario 1: one road with a single traffic light

The objective of the first scenario presented in this section is to identify key influencing factors on the performance metrics described in section 5.2, and to quantify the extent of their effect.
The most basic scenario is used in order to exclude the potential influence of the road topology on the performance of the system. Definitely the most basic scenario is built up by a single-road with one traffic light and one RSU. In reality, this is a typical scenario for a traffic light controlling a pedestrian crossover on a basic road. Obviously, such type of TLC does not require the high information update rate as defined in section 3.4, nevertheless we use different information update rates to provide first insights in the basic performance of the system. Figure 5.1 provides a schematic overview of the scenario.

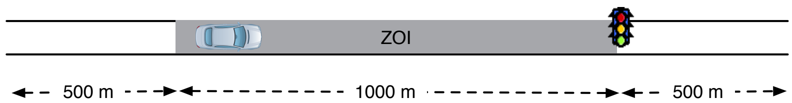


Figure 5.1: One road with a single traffic light

The scenario is built up by one road in one direction with a total length of 2000 m and is divided by a traffic light controlled intersection into two road segments: 1500 m before the intersection and 500 m after the intersection.
The road segment in front of the intersection with its length of 1500 m sufficiently exceeds the required ZOI length of 1000 m (section 3.4). The ZOI in figure 5.1 is marked with a gray color. The number of lanes is increase across the experiments to increase the number of vehicles within the ZOI. For this scenario, we start with a series of experiments with a road consisting of 2 lanes while varying the parameters of table 5.1, and continue with a series of experiments with a road consisting of 20 lanes.

Scenario 2: crossroads connected by a single traffic light

The scenario in this section models again one intersection with one RSU, but with additional roads. The main differences with the previous scenario is an increase in vehicles added by the crossroad and vehicles coming from opposite direction of the same road.
Figure 5.2 depicts a schematic overview of the scenario. Each road consists of two times 3 lanes in opposites directions with a total length of 3000 m and is dived by a traffic light controlled intersection. All vehicles approaching the intersection within the range of 1000 m from the intersection belong to the ZOI. In figure 5.2 the ZOI is marked with a gray color. For simplicity, the destination of every vehicle is at the end of the road it has started, thus every vehicle follows a straight line. However, with the availability of multiple lanes and the mobility model defined in table 5.2, overtaking can be expected.

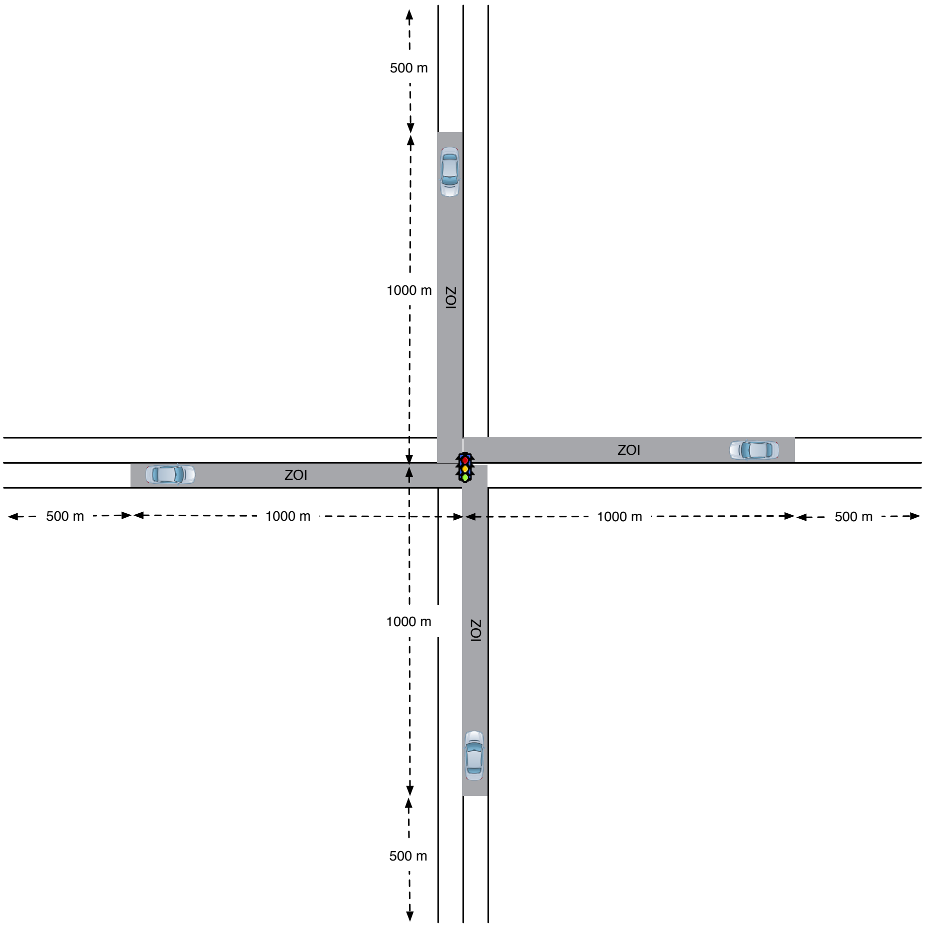


Figure 5.2: crossroads with a single traffic light

Scenario 3: cascade of traffic lights

The objective of this third and last scenario is to investigate the influence of a cascade of RSUs. The scenario is depicted in figure 5.3. As can be seen, the scenario comprises one road with two cascaded TLC controlled intersections. The distance between the two RSUs is 500 m. In contrast to scenario 1, this road includes a two-directional road.

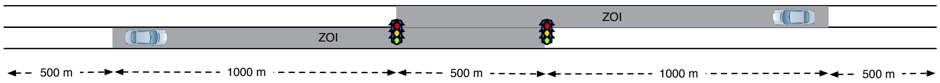


Figure 5.3: One road with a single traffic light

5.4 Results analysis

This section describes the results of the simulation study. As stated before, the goal of the simulation study is to quantify the effects of the influencing factors (described in section 5.1) on the performance metrics (described in section 5.2). For each scenario described in the previous section 5.3.2 we describe the following metrics: utilization, notification distance, delivery ratio en end-to-end delay. These metrics have been briefly described in section 5.2. Since the result of any network simulator is a random sample, statistical methods have been used to evaluate the results. Usually one random sample is not enough to confidentially evaluate the results. Thus, each experiment have been performed several times, each initialized with a different run number for the RNG. The results of these runs are then combined by calculating the average results and showed as means in the figures of the next sections. For all shown results, the confidence intervals of the averages have been left out, but the calculated 95% confidence intervals are lower than 5% of the shown averages.

5.4.1 Scenario 1: one road with a single traffic light

The goal of the experiments conducted with this first scenario is to quantify the effects of the vehicle density, mobility, transmission range, and packet size on the performance of the system (i.e. quantifying the metrics). This first scenario is built up by one road in one direction with 20 lanes, a total length of 2000 m and is divided by a traffic light controlled intersection into two road segments: 1500 m before the intersection and 500 m after the intersection (see figure 5.1).

Since we have been testing a realistic scenario with realistic driving behaviour supported by the Krauß-mobility model, the maximum vehicle density per lane is restricted by the vehicle length and the safety distance between the vehicles. Based on some simple tests with an one-lane road and a vehicle length of 5 m (see table 5.2), we found an average vehicle density of 25 vehicles/km/lane for a maximum speed set to 70 km/h, an average vehicle density of 35 vehicles/km/lane for a maxim speed set to 50 km/h, and an average vehicle density of 60 vehicles/km/lane for a maxim speed set to 30 km/h. The vehicle density increased when we introduced queues in front of the traffic light (by increasing the red light period). As mentioned in the description of the application in section 3.3, though not guaranteed the CTLA application aims a continuous flow of traffic. With the lower bound speed of 30 km/h (see section 3.3) the vehicle density per km lane is restricted to 60 vehicles. However, the experiments could result in higher vehicle densities in case the vehicles have to wait in front of the traffic light. Therefore, we measured the vehicle density per experiment.

Common channel utilization

The parameters that have a significant impact on the common channel utilization (from now referred as utilization) is the vehicle density and the transmission range.
Figure 5.4 depicts the average utilization of the three dissemination protocols for a 20 lanes one-road scenario with the maximum speed set to 50 km/h and the transmission range set to 350 m (23 dBm). For readability, the one-to-zone dissemination protocol described in section 4.2 is labelled as *broadcast*, the one-to-one dissemination with RSU-CAM trigger described in section 4.3 is labelled as *unicast1*, and last the one-to-one dissemination with vehicle-CAM trigger described in section 4.4 is labelled as *unicast2*.
Recall from our description of the *common channel utilization* performance metric in section 5.2 that the utilization is the total load added by the message exchange of the CTLA application as well as the CAMs of the beaconing service. As can be seen in the figure, all protocols follow a same trend in case

of an increasing vehicle density: as the density increases the utilization increases as well. The broadcast protocol shows a higher utilization compared to the unicast protocols. This can be explained by larger xml message which is disseminated by the broadcast protocol and is forwarded by the microslotted-1-persistence protocol. The utilization of both the unicast protocols is more or less equal.
Besides a transmission range of 350 m, we conducted the same experiments with a transmission range of 900 m. In this case, all the protocols showed a slightly more utilization than in the case of the 350 m transmission range. This effect corresponds to our intuition that a higher transmission range results in an increase of the medium busy time notified by the average vehicle, because in this case more vehicles are able to receive a signal of another node.

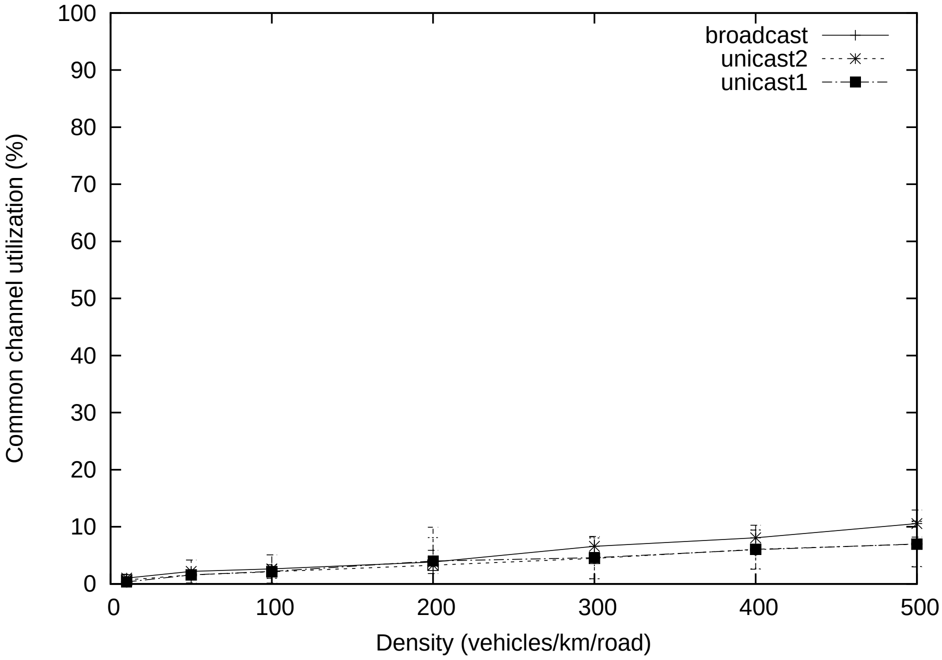


Figure 5.4: Common channel utilization of 3 dissemination protocols for a 20 lanes one-road scenario, with transmission range set to 350 m

The second figure 5.5 shows the utilization for a vehicle densities with same settings as in figure 5.4, but now we increased the payload size of the broadcast message to 10 kb. The trend of the figure seen in the figure 5.4 with a broadcast payload size of 2 kb can again be observed in figure 5.5. However, the broadcast protocol shows - as expected - a slightly more utilization than in the previous case with a payload of 10 kb.

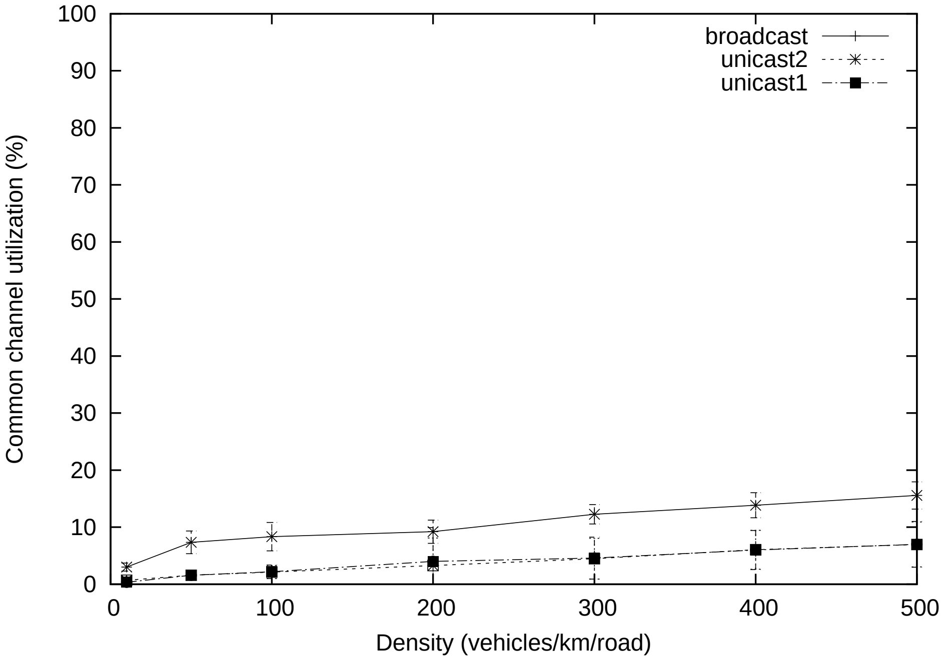


Figure 5.5: Common channel utilization of 3 dissemination protocols for the same scenario as in figure 5.4, but with the payload size of the broadcast message set to 10 kb

Notification distance

The parameter that has the most impact on the notification distance of the unicast protocols is the transmission range. Both the effect of varying the vehicle density on all protocols, and the effect of varying the transmission range on the broadcast protocol was found not to be significant.
Figure 5.6 depicts the notification distances of the three dissemination protocols for the on-road scenario with 20 lanes and a vehicle density of 50 vehicles/km/road, with transmission range set to 350 m. The figure illustrates the number of vehicles that receive the first CTLA message as a function of the distance to the RSU, i.e. the y-axis shows the number of vehicles per chunk of 50 m and the x-axis shows the distance to the RSU in chunks of 50 m. Note that the x-asis represents the length of the ZOI which equals to 1000 m.
As can be seen in the figure, the average number of vehicles that receive the first message in chunk differs for each protocol. For both unicast protocols, the average vehicle receive the first message in chunk 250 m (i.e., between 250 m en 300 m). It holds for both unicast protocols that the application is triggered by a CAM advertisement, which is - depending on the protocol - a CAM advertisement of the vehicle or a CAM advertisement the RSU. This CAM message is not forwarded by any multi-hop protocol, thus the maximum notification distance of both unicast protocols is restricted by the transmission range used to send the CAM advertisement, which equals to 350 m in this scenario. After receiving a CAM (on average in chunk 300 m for both unicast protocols which equals to the transmission range used in this scenario) an unicast transmission is started. As can be seen in figure 5.6, upon receiving the first message, the average vehicle is in chunk 250 m.
A second observation about the unicast protocols is that with the first unicast protocol with RSU-CAM trigger (labelled unicast1 in the figure), the number of vehicles that receive a first message in chunk 300 m is lower than the in the case of the second unicast protocol with vehicle-CAM trigger (labelled unicast2 in the figure). This can be explained because of the added message exchange between RSU and vehicle (see figure 4.2); upon receiving the second message in this exchange patter, there is a higher chance that the vehicle is chunk 250 m.
Finally, with the broadcast protocol the vehicles on average receive the first message between 950 m and 1000 m from to the RSU, which equals to maximum distance of the ZOI. In contrast to the unicast protocols, the broadcast protocol does not use a CAM to advertise its service: the CTLA message is

send to all the vehicles within the transmission range. Vehicles that receive this message use the micro-slotted-1-persistence forwarding scheme (described in section 4.4) to forward the messages within the ZOI. As a result, on average the first message for the broadcast protocol is received at the maximum distance of the ZOI.

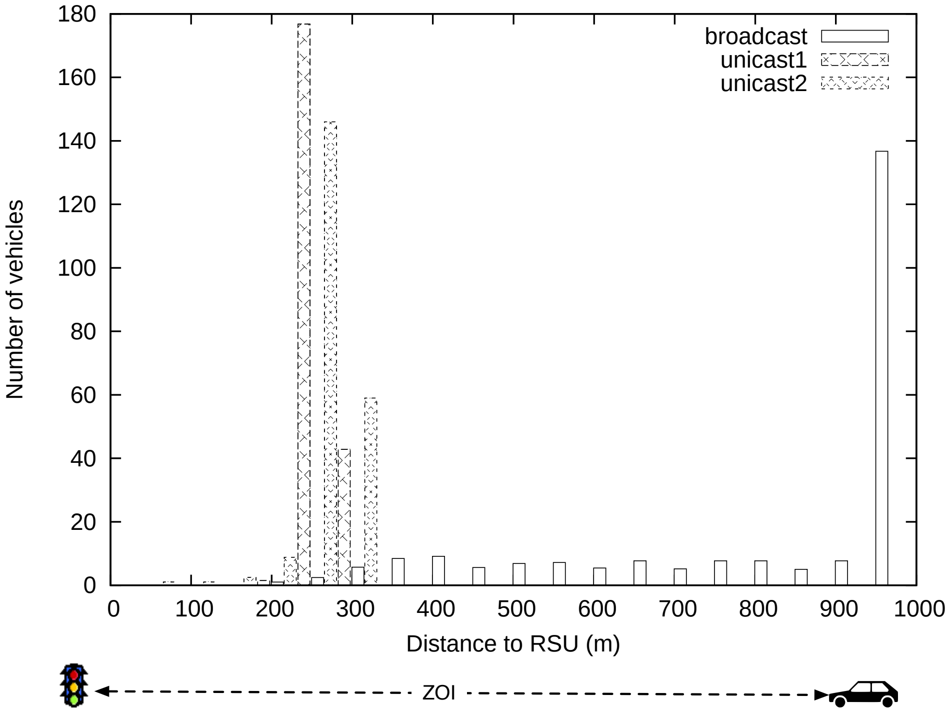


Figure 5.6: Notification distances of 3 dissemination protocols for a 20 lanes one-road scenario, with transmission range set to 350 m

Figure 5.7 shows the notification distances with the same settings of figure 5.6, but now with the transmission range set to a higher distance of 900 m. As can bee seen in the figure, the notification distance of the broadcast protocol shows a similar trend as with the 350 m transmission range. This can be explained by the micro-slotted-1-persistence forwarding protocol which functions efficiently with different transmission ranges. Furthermore it can be observed that the notification distance of both unicast protocols in figure 5.7 has shifted to chunk 850 m, compared to the notification distances of figure 5.6. This can easily be explained by the higher transmission power used in this experiment.

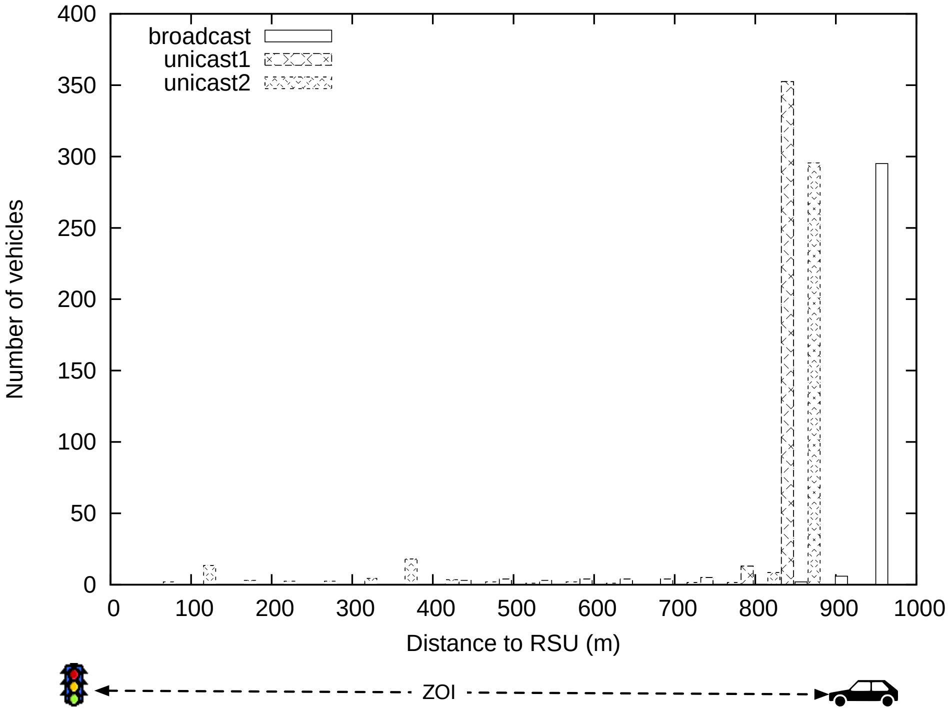


Figure 5.7: Notification distances of 3 dissemination protocols for a 20 lanes one-road scenario, with transmission range set to 900 m

Delivery ratio

The parameter that has the most impact on the delivery ratio is the vehicle density. The effect of varying the transmission range on the delivery ratio was found not to be significant.
Figure 5.8 shows the delivery ratio of a 20 lanes one-road scenario with transmission range set to 900 m. As can be seen in the figure 5.8, all protocols follow a same trend in case of an increasing vehicle density: if the vehicle density increases, the delivery ration decreases.
In general, the delivery ratios for the unicast protocols are higher than 95 % and the delivery ratios for the broadcast protocol is higher than 90 %. The lower delivery ratio for the broadcast protocol can be explained by the higher packet size and the forwarding protocol used, which both increase the possibility of collisions.

Figure 5.9 shows again the delivery ratio, but now as a function of the vehicle's distance to the RSU. This figure has been constructed with a vehicle density of 100 vehicles/km/road and a transmission range of 800 m. As can be seen in the figure the delivery ratio for the unicast protocols is almost 100% in every chunk. The broadcast protocol shows the same results for distances to the RSU below 500 m, but starts to decrease in case of higher distances. This trend was found in general for higher vehicle densities. This behaviour can be explained that although we have been using the micro-slotted-1-persistence forwarding protocols to prevent the synchronization problem in the same slot (see section 4.4), the number of vehicles in slots at the end of the ZOI is higher which results in more packet collisions.

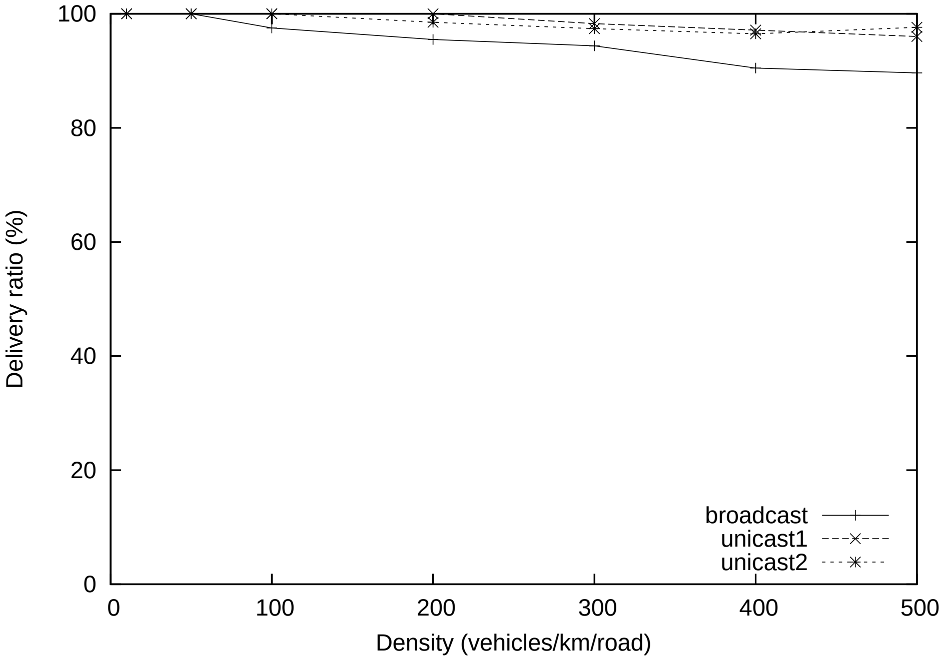


Figure 5.8: Delivery ratios of 3 dissemination protocols for a 20 lanes one-road scenario, with transmission range set to 900 m

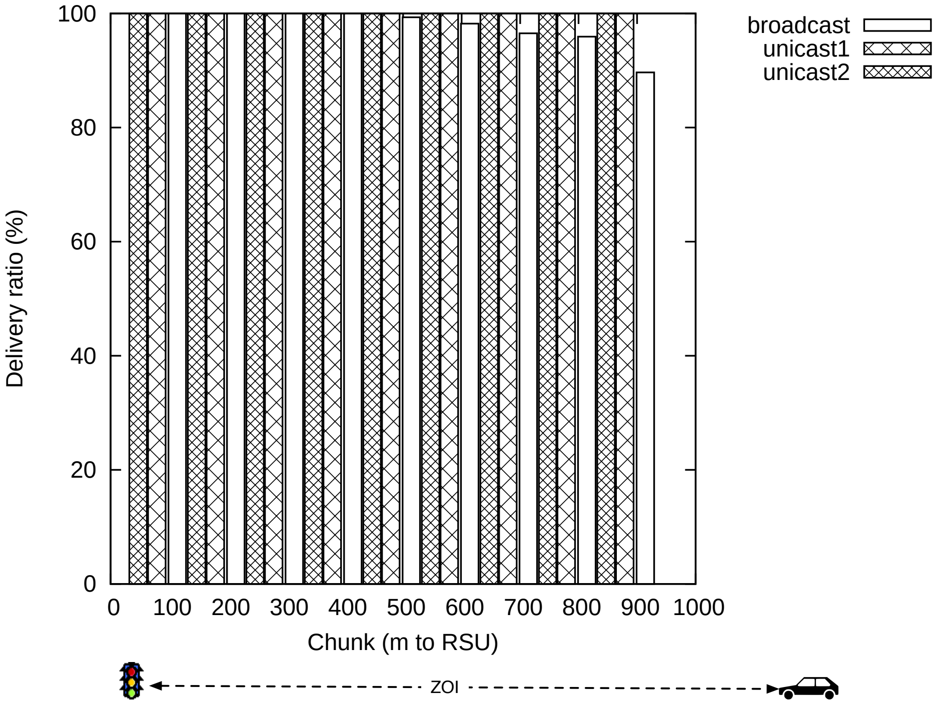


Figure 5.9: Delivery ratios (as a function of the distance to the RSU) of 3 dissemination protocols for a 20 lanes one-road scenario, with vehicle density 100 vehicle/km/road and transmission range set to 900 m

End-to-end delay

The parameter that has the most impact on the end-to-end delay (from now referred as delay) is the vehicle density. The effect of varying the transmission range on the delay was found not to be significant.

Figure 5.10 depicts the average delay for the one-road scenario with 20 lanes. It can be observed that, for all protocols, an increasing density results in an increase of the delay. This can be explained by the fact that higher vehicle densities results in a more congestion situation on the wireless channel. Consequently, there are more retransmissions resulting in an increased delay.
A second observation is that the unicast protocol with RSU-CAM trigger shows larger delay values than the other two protocols. This can be explained by the fact that this protocol includes two-way communication, in contrast to the one-way communication of the other two protocols (as explained in chapter 4). Furthermore, the delay of the broadcast protocol shows the lowest delays, because this includes only the delay of the periodic message which is broadcasted to all vehicles. The delay of both unicast protocols in figure 5.10 is the sum of the delay caused by all the transmissions between every vehicle and RSU. Finally, it can be noted that even in the case of a high vehicle density, the average delay of all tested protocols is below 300 ms.

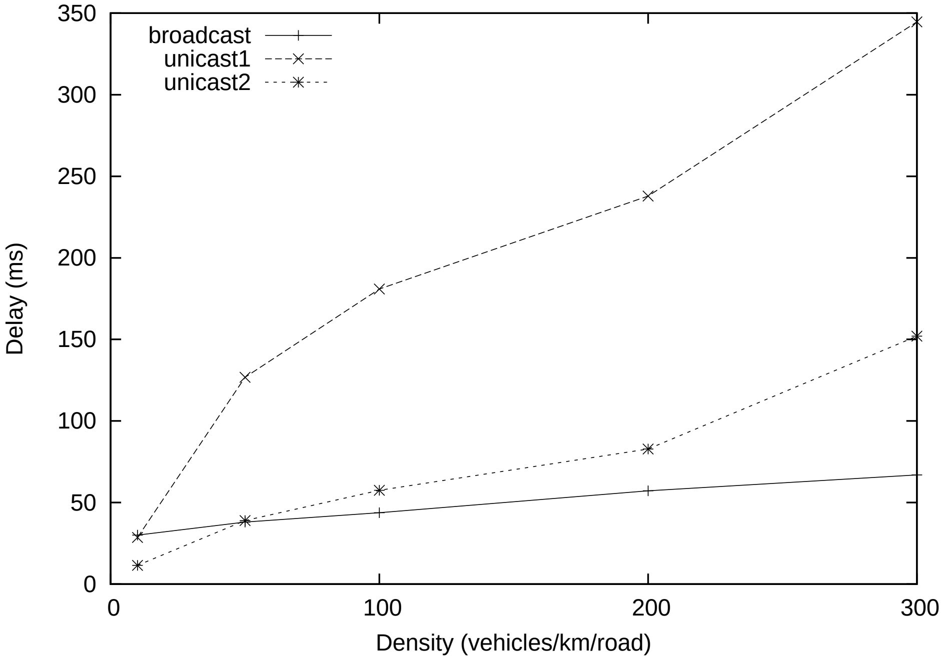


Figure 5.10: Delay for a 20 lanes one-road scenario

Figure 5.11 shows again the average delay of the protocols, but now as a function of the vehicle's distance to the RSU. This figure has been constructed with a vehicle density of 200 vehicles/km/road and a transmission range of 350 m. As can be seen in the figure the delay for the unicast protocol with RSU-CAM trigger shows the largest delay for distances less than 350 m to the RSU. For distances greater than 350 m to the RSU, the delay of the broadcast protocol start to increase almost linearly in propitiation with the distance to the RSU. This can be explained by the broadcast multi-hop mechanism which forwards messages with some additional delay.

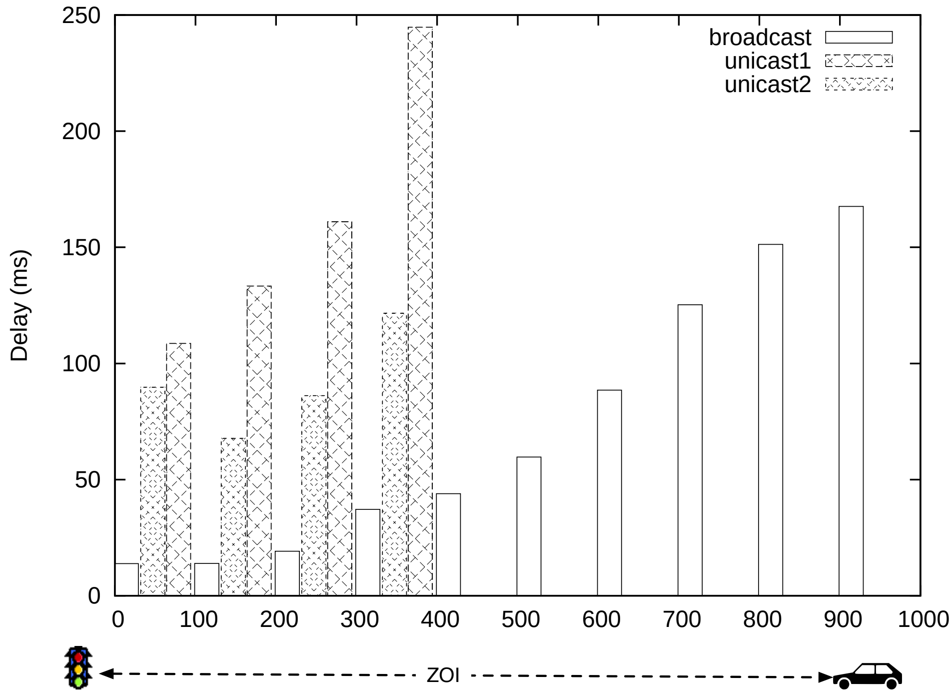


Figure 5.11: Delays (as a function of the distance to the RSU) of 3 dissemination protocols for a 20 lanes one-road scenario, with vehicle density 200 vehicle/km/road and transmission range set to 350 m

5.4.2 Scenario 2: crossroads connected by a single traffic light

The results of the first scenario provided us the insights in the performance of the system for the most basic scenario. In addition the influences of the mobility and transmission range has been investigated. In this second scenario, we are going to determine the influence of the vehicle density in a crossroad scenario. The main differences with the one road scenario of the previous scenario, is the addition of vehicle traffic coming from the opposite direction and the addition of a crossroad (see figure 5.2). As with the first scenario, each road has a length of 2000 m and is divided by a traffic light controlled intersection into two road segments: 1500 m before the intersection and 1500 m after the intersection. Every road consists of 3 lanes in opposites directions which makes a total of 6 lanes per road. Only vehicles approaching the intersection are part of the ZOI, thus vehicles which already passed the intersection will dismiss a received package.

Common channel utilization

It was found that the crossroad topology did not influence the average utilization of all three protocols. Figure 5.12 depict the utilization of a 6 lanes crossroad scenario, with transmission range set to 300 m. If we compare these results to the results of figure 5.5 we observe a similar trend for all three protocols. However, the figure 5.12 shows a slight larger utilization for each vehicle density, which can be explained by the addition of the opposition road causing a high utilization.

Notification distance

It was found that the crossroad topology did not influence the average notification distance of all three protocols.
Figure 5.13(a) shows the notification distances for the crossroad scenario with 6 lanes, with a transmission range set to 800 m (5.13(a)) and with a transmission range set to 300 m (5.13(b)). If we compare these

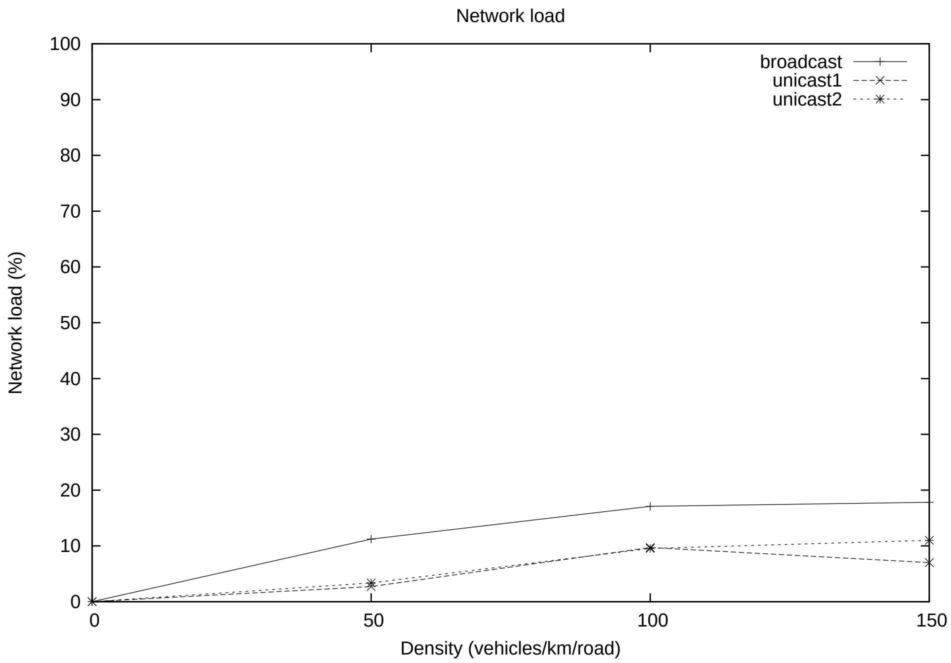
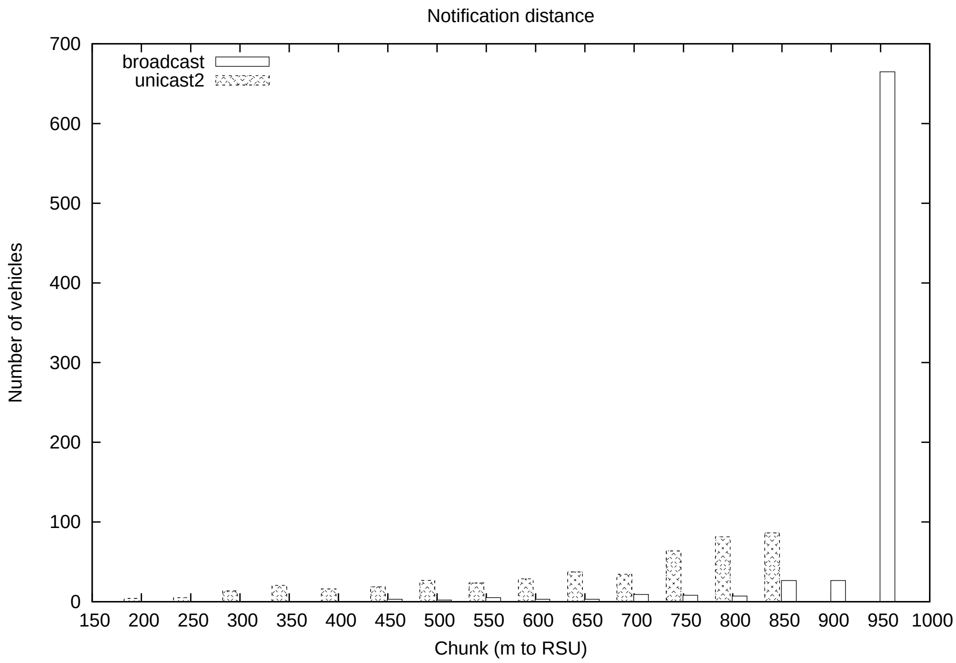


Figure 5.12: Common channel utilization of the 3 dissemination protocols for a 6 lanes crossroad scenario with transmission range set to 300 m

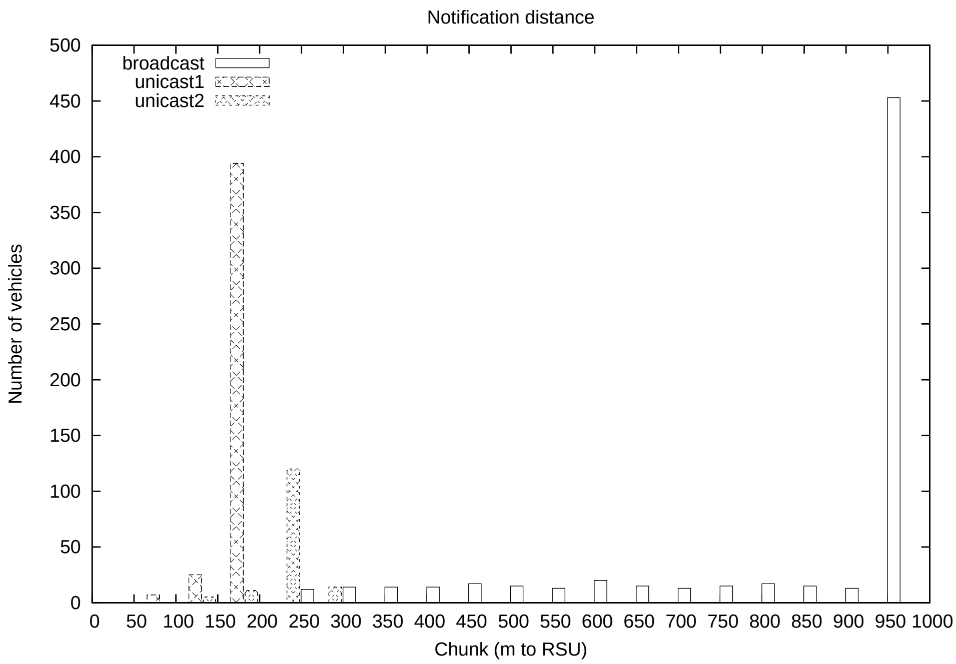
results to the result of section 5.4.1 we observe a similar trend for all three protocols. This can be explained that the difference with the previous scenario is only the added road and the opposite road segment, which does not average influence the notification distance.

Delivery ratio

It was found that the crossroad topology did not influence the average delivery ratio of all three protocols. Figure 5.14 shows the delivery ratios as a function of the vehicle's distance to the RSU for the 6 lanes crossroad scenario. Both figures have been constructed with a 6 lanes scenario, but with different transmission ranges and vehicle densities
Figure 5.14(a) depicts the delivery ratio of the scenario with vehicle density 50 vehicles/km/road and a transmission range of 800 m. As can be seen in the figure the delivery ratio for the unicast protocols is almost 100% in every chunk. The broadcast protocol shows some lower delivery ratios a all chunks, which can be explained that these experiments caused several queues at the intersection.



(a) transmission range set to 800 m

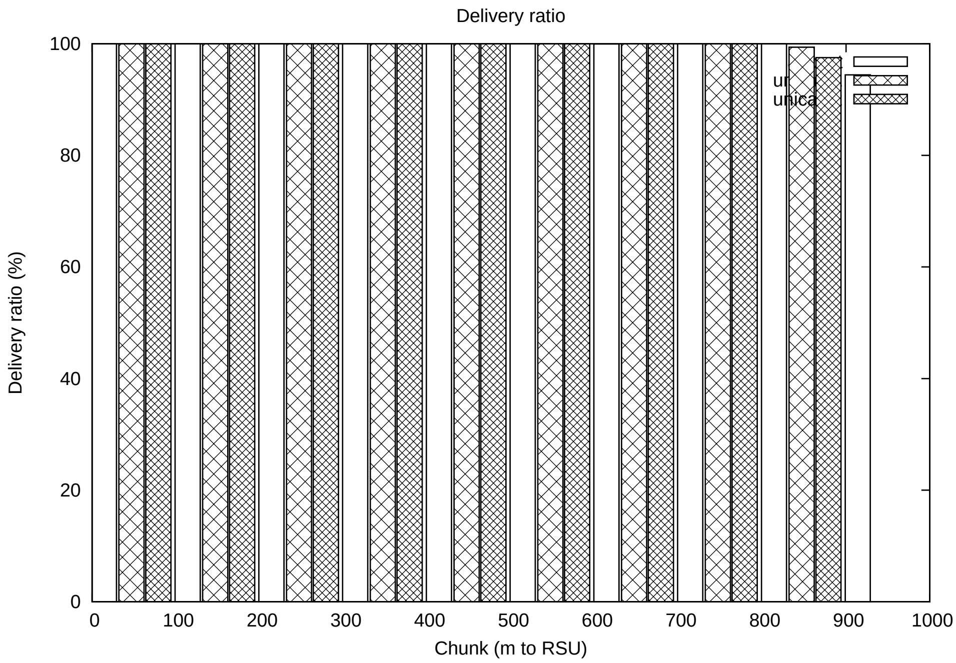


(b) transmission range set to 300 m

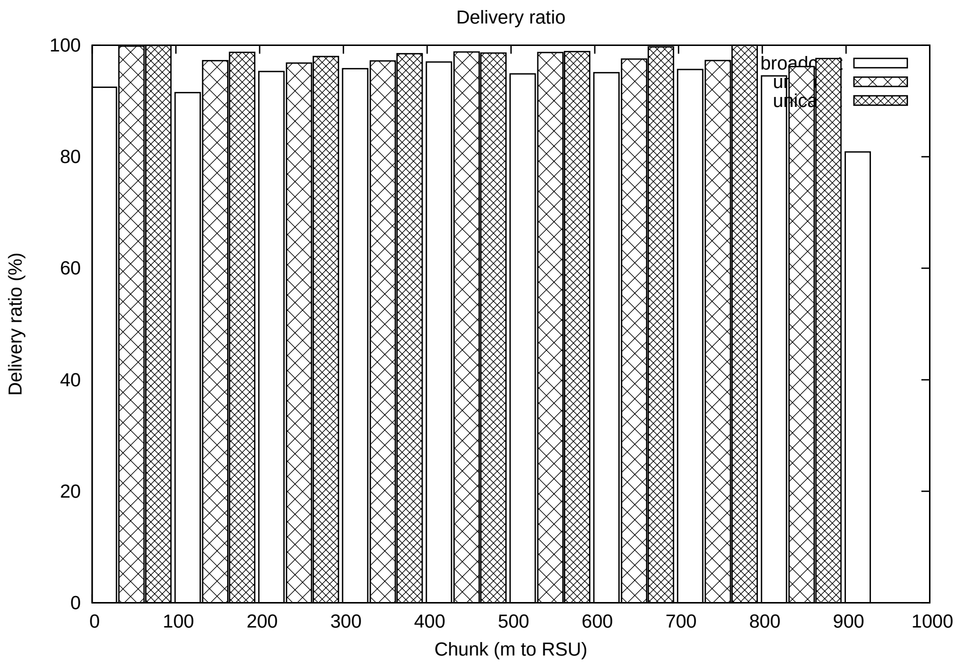
Figure 5.13: Notification distances of the 3 dissemination protocols for a crossroad scenario with 6 lanes

End-to-end delay

It was found that the crossroad topology did influence the average end-to-end delay of all three protocols. Figure 5.15 shows the delays as a function of the vehicle's distance to the RSU for the 6 lanes crossroad scenario. The figure has been constructed with a 6 lanes scenario, but with different transmission ranges. It can be observed that this crossroad scenario results of figure 5.15 shows a higher delay for all chunks



(a) vehicle density 50 vehicles/km/road, with range set to 800 m



(b) vehicle density 300 vehicle/km/road, with range set to 800 m

Figure 5.14: Delivery ratios of the 3 dissemination protocols for a crossroad scenario with 6 lanes compared to the one-road scenario results of the sub-figures in figure 5.11.

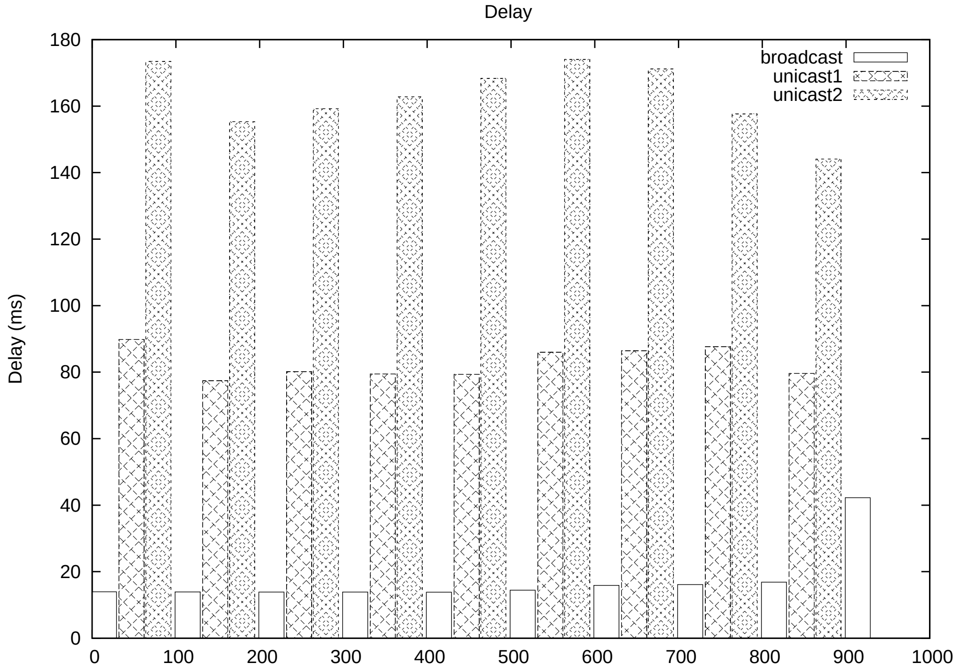


Figure 5.15: Delay of the 3 dissemination protocols for a 6 lanes crossroad scenario with transmission range set to 900 m

5.4.3 Scenario 3: cascade of traffic lights

In this last scenario, we are going to determine the influence of a second RSU in a crossroad scenario. The main difference with the previous crossroad scenario, is the addition of a second TLC controlled intersection with its connected road as can be seen in figure 5.3. Both RSUs are placed with a distance of 500 m of each other. Since we are investigating the influence of a cascade of RSUs, we choose a transmission range of 800 m for our experiments to make sure that there is a overlapping transmission range between the two RSUs. The horizontal road has a total length of 3500 m with an intersection placed at 1500 m from the left and the second intersection placed 2000 m from the left (and 1500 m from the right).

Common channel utilization

It was found that the cascaded RSUs did not influence the average utilization of all three protocols.
Figure 5.16 depict the utilization for the scenario with 6 lanes, with a transmission range set to 800 m. If we compare these results to the results of figure 5.4 and 5.12 we observe a similar trend for all three protocols.

Notification distance

It was found that the cascaded RSUs did not influence the average notification distance of all three protocols.
Figure 5.4.3 shows the notification distances for the scenario with 6 lanes, with a transmission range set to 800 m. If we compare these results to the results of section 5.4.1 we observe a similar trend for all three protocols.

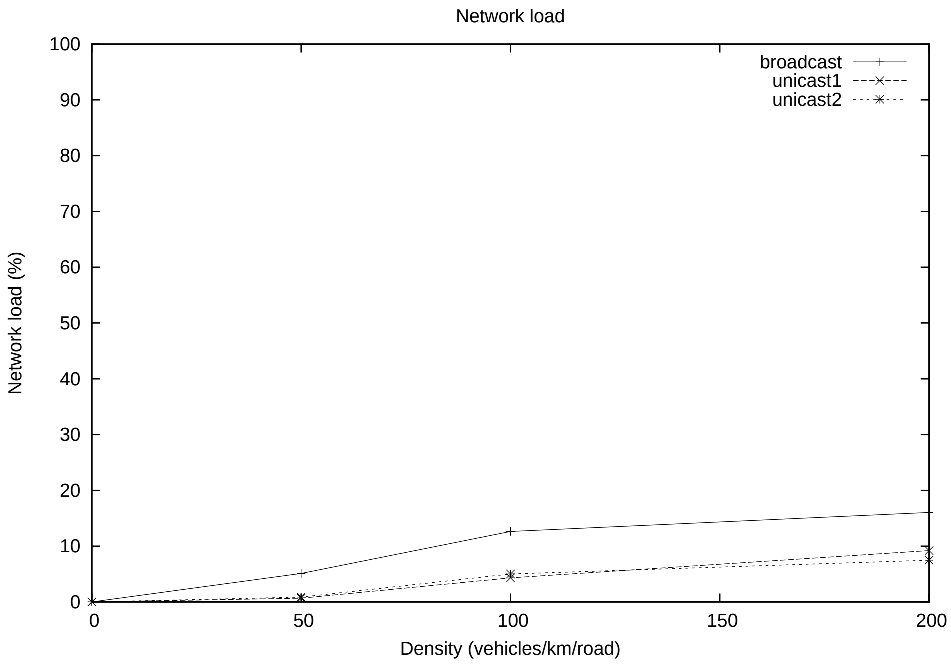


Figure 5.16: Utilization for 6 lanes cascaded RSUs scenario, with a transmission range set to 800 m

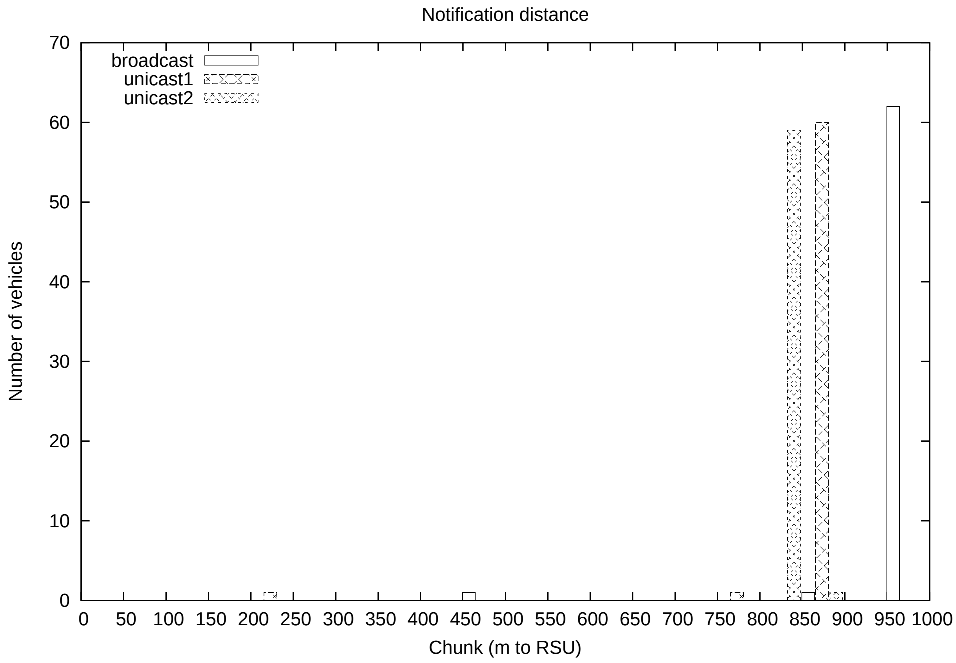


Figure 5.17: Notification distances for a cascaded RSUs scenario with 6 lanes

Delivery ratio

It was found that the cascaded RSUs did not influence the average delivery ratio of all three protocols. Figure 5.4.3 shows the delivery ratios as a function of the vehicle's distance to the RSU for the 6 lanes cascaded RSUs scenario. As can be observed, the delivery for all protocols almost equals 100% for all chunks. If we compare these results to the results of figure 5.4.3 with figure **??** we observe a similar trend for all three protocols.

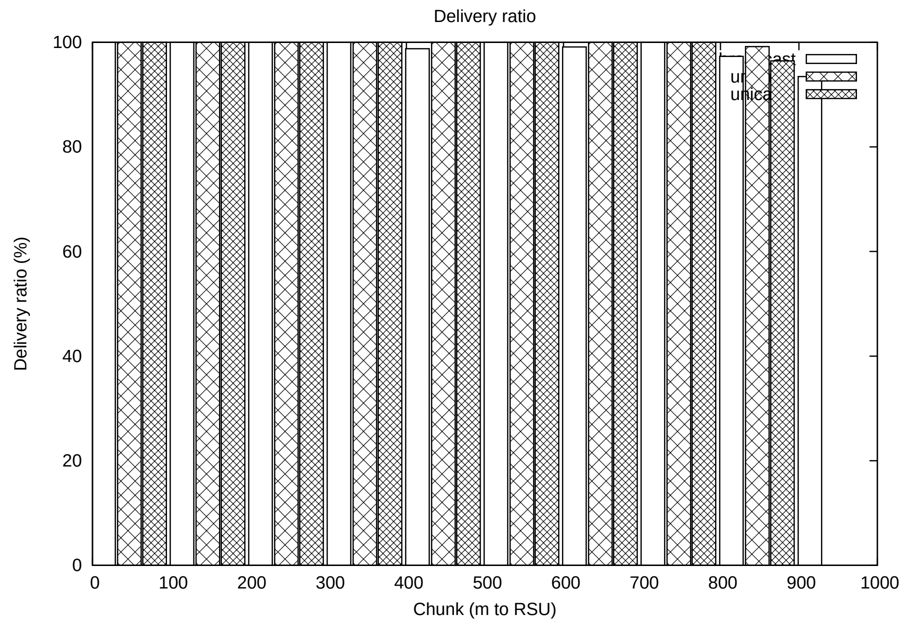


Figure 5.18: Notification distances for a cascaded RSUs scenario with 6 lanes

End-to-end delay

It was found that the cascaded RSUs did influence the average end-to-end delay of all three protocols. Figure 5.4.3 shows the delay as a function of the vehicle's distance to the RSU for the 6 lanes cascaded RSUs scenario.
It can be observed that the figure 5.4.3 shows a higher delay for all chunks compared to the one-road scenario results of figure 5.11.

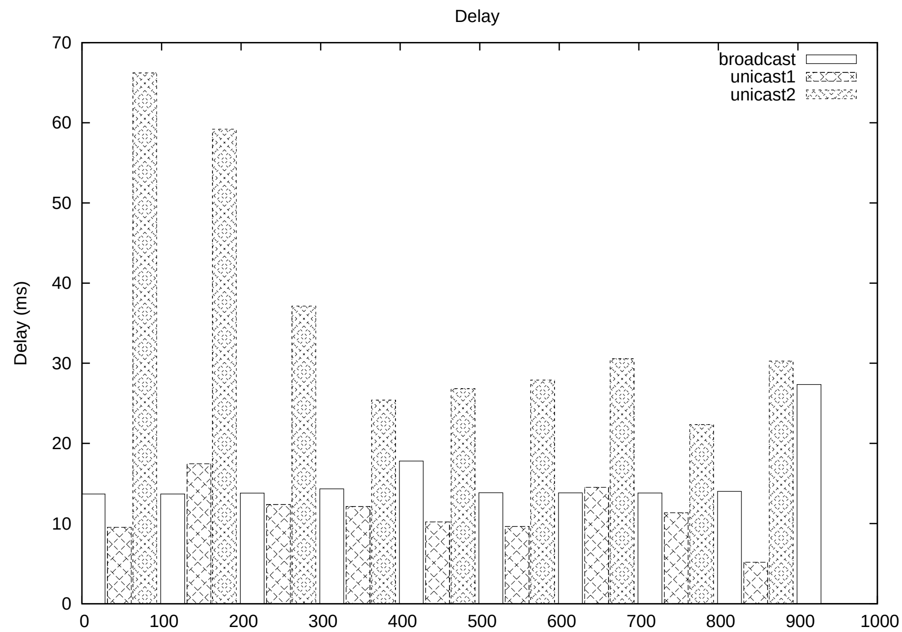


Figure 5.19: Notification distances for a cascaded RSUs scenario with 6 lanes

5.5 Summary

This chapter described the results of the simulation experiments of the dissemination protocols for the CTLA application. All experiments have been performed by means of simulations in the VANET simulator iTETRIS (see section 2.4.2).
It was showed that the dissemination distance had - though small - influence on the results. As expected, the vehicle density increased every performance metric. Finally, it was found that the topology did not significantly influence the performance of the protocols. The next chapter discuss the results of this chapter in relation with the requirements of the CTLA application and provides several conclusions.

Chapter 6

Conclusion

Having described the results of the performance study in chapter 5, we end this research with a conclusion of the results. First, in section 6.1 we provide a brief overview of this research and present the main findings of the results. Then, in section 6.2 we provide the answers to the research questions stated in the introduction chapter 1. In section 6.3, based on the conclusions, we provide recommendations for the usage of the CTLA application. We end this chapter with several notes about future work.

6.1 Overview

Throughout this research we investigated the wireless Infrastructure-to-Vehicle (I2V) communication of a traffic-light application. Based on the *Speed advice application* - which has been used in different studies about I2V applications - we specified the CTLA application: a traffic efficiency application that enables a RSU to send both an individual speed advice to a vehicle and the traffic light planning of a connect Traffic Light Controller (TLC). In addition, we designed three dissemination protocols that are able to exchange the application data between a vehicle and a RSU. It was found that such a type of application requires the definition of a Zone of Interest (ZOI): a geographic area in which all vehicles located in that area should be informed. Addressing based on geo-cast proved to be a suitable networking protocol to address the vehicles in the ZOI.
In order to provide results that represents realistic scenarios, we identified the influencing factors that influence the I2V communication. It was found that vehicle density was the most influencing factor on the wireless channel and that different transmission ranges result in slightly different performances. The road topology, however, was found not be an significant influencing factor.
We decided to perform the simulation experiments by means of the iTETRIS simulator, based on its complete implementation of the CALM architecture and its high level of realism thanks to the incorporated traffic simulator SUMO. Mainly because iTETRIS was at the beginning of this research still under heavy development, we faced a lot of problems. Nevertheless, we managed to implement the CTLA application, all of its three dissemination protocols, and to perform large scale simulations. Unfortunately, at time of running the simulations, performing parallel simulations on one machine was not possible because ns-3 did not supported parallelism and simulations took much longer than expected.

6.2 Answers to the research questions

Throughout this study, we have provided the answers to the research questions stated in the introduction chapter 1. This section provides a brief answer to these questions.

- **What are the requirements of the Cooperative Traffic Light Assistant (CTLA) application?**
  The requirements can be categorized as application requirements, communication requirements,and performance requirements. First, for the application requirements it was found that such a type of application requires the definition of a Zone of Interest (ZOI): a geographic area in which all vehicles located in that area should be informed. Although some related projects used ZOI which was defined by the RSUs transmission range, there was no argumentation in term of traffic efficiency to use this range. Therefore we assumed vehicles approaching the traffic light within 1000 m to be part of the ZOI. Assuming a realistic scenario, we noted that vehicles by default are not aware of a RSU and its services. Therefore, we used the CAM advertisement mechanism to inform vehicles about the RSU's presence and its services. Thus, this implies the existence of a CAM service. Furthermore, we assumed that every vehicle was equipped with the CTLA application and that a basic speed advice calculation algorithm was able to calculate a correct speed advice.
  Second, for the communication requirements we stated that the ETSI reference architecture with the IEEE-802.11p/ITS-G5 was used. Though it is reasonable to assume that the CTLA application could operate with a different communication technology, this research was restricted to investigate only this technology. One of the advantages of using the ETSI reference architecture was its built-in support for geo-addressing.
  Finally, we defined the following performance requirements, which aim at using the most efficient solution with the maximum number of vehicles:
  - The application should be used by the maximum number of vehicles without experiencing significant loss in performance
  - Within the ZOI, a vehicle should be travelling as much as possible with the most up to date application data
  - The application should be usable in every kind of vehicular environment, e.g. urban, suburban, highway
  - The system should use the minimum load on the medium without harming the other requirements
- **Which data should be exchanged between vehicles and Road Side Units (RSUs) and what are the exchange patterns?**
  We defined the CTLA as an application that can exchange both an individual speed advice and the traffic light schedule of the TLC. It was found that these data types implied the exchange patterns. First, sending a individual speed advice to a vehicle corresponds an one-to-one dissemination patten. Second, if the vehicle is equipped with a speed advice calculation algorithm, than the RSU should send the traffic-light schedule, which corresponds to either a one-to-one dissemination pattern or an one-to-zone dissemination pattern.
  Based on the responsible node for the speed advice calculation and the application trigger condition, we defined three dissemination protocols: two protocols with an one-to-one dissemination pattern which uses unicast geo-routing as the routing technology and an one-to-zone dissemination pattern which uses geo-broadcast routing as the routing technology. The two unicast protocols are distinguished by the node which advertise the service (by means of the CAM), which is either the vehicle or the RSU.
- **To what extend is the Cooperative Traffic Light Assistant (CTLA) system scalable?**
  With the settings we have been testing the system, the CTLA is scalable. Recall from the definition of scalability that scalability is defined as "the ability to handle the addition of vehicles without suffering a noticeable loss in performance or increase in administrative complexity". In the following we briefly discuss the performance requirements.
  The first performance requirement stated that the application should be used by the maximum

number of vehicles without experiencing significant loss in performance. It was argued that the theoretical maximum number of vehicles of a road is restricted by the vehicle length, the minimun vehicle distance and the number of lanes. In addition, the theoretical maximum number of vehicles passing an intersection is around 1800 vehicles/hour. In order to reach a vehicle density of 500 vehicles/km/road with the Kraußmobility-model of SUMO, we had to increase the number of lanes of the one-road scenario of section 5.3.2 to 20 lanes. It was showed that for all of the three dissemination protocols, the performance in terms of the metrics notification distance, delivery ratio, and delay where still acceptable.
The second performance requirement stated that within the ZOI, a vehicle should be travelling as much as possible with the most up to date application data. Because the one-to-zone (i.e. broadcast) dissemination protocol, with its multi-hop protocol, covers the whole ZOI, it would be obvious to state the broadcast protocol meets this requirements the best. However, we used a ZOI length which was larger than the tested transmission ranges. If, for example, the ZOI length is set to 300 m, both one-to-one (i.e., unicast) dissemination protocols are suitable as well. Moreover, in this context, it was found that the one-to-one dissemination protocol with vehicle-CAM trigger outperforms the other one-to-one dissemination protocol.
The third performance requirement stated that the application should be usable in every kind of vehicular environment, e.g. urban, sub-urban, highway. We differentiated between these environments by varying the maximum vehicle speed and the transmission range. It was showed that for all dissemination protocols the performance - in terms of our metrics - was acceptable.
The last performance requirement stated that the system should use the minimum load on the medium without harming the other requirements. The results showed that the common channel utilization for all of the three protocols followed a same trend when increasing the vehicle density. The broadcast protocol showed a slight higher channel load, which was because of the large package size used for the broadcast message. Both of the unicast protocols provided to utilize the minimum load on the medium while still respecting the other requirements.
We end this answer with a final note to emphasize that the system is scalable with the settings we have used. For example, we have tested the system with a beacon update rate of 1 Hz, some applications might require a higher update rate which consequently results in an higher channel load. The future work section 6.4 provides some additional notes about this

- **Which dissemination protocol can be advised as the optimal protocol for the CTLA application?**
As also will be recommended in the next section, the dissemination protocol should be based on the requirements. If, for example, the RSU should be in control of determining the vehicle speed advice (which seems reasonable if the vehicles are not able to deal with complex traffic-light schedules), an one-to-one dissemination strategy should be chosen. On the other hand, if the length of the ZOI is required to be larger then the maximum range of which a RSU can disseminate its CAM advertisement, an one-to-zone dissemination strategy should be chosen. Since all dissemination protocols proved to be scalable, non of these protocols can be rejected based on the performance.

6.3 Recommendations

Based on the conclusions of the previous section, this section provides the following recommendations for using the CTLA system:

- The dissemination protocol of such an application should be carefully chosen based on the requirements. If, for example, the RSU should be in control of determining the vehicle speed advice (which seems reasonable if the vehicles are not able to deal with complex traffic-light schedules), an one-to-one dissemination strategy should be chosen. On the other hand, if the length of the ZOI is required to be larger then the maximum range of which a RSU can disseminate its CAM advertisement, a one-to-zone dissemination strategy should be chosen.

- All participants in an ITS scenario should use standardized technologies. This research showed that the microslotted-1-persistence multi-hop could increase the information dissemination range of the RSUs. However, this is only possible if the forwarding vehicles are able to forward the data. This can be achieved by using standardized technologies.

- A system using speed advises should be as accurate as possible. It is reasonable to expect that if the system most often provides wrong advices, drivers will ignore the advice. Therefore, the advised speed should be as accurate as possible. The findings of this research about the wireless communication can be used to create an algorithm that takes the performance of the wireless communication into account.

6.4 Future work

This research contributed to research in the field of I2V communication with IEEE 802.11p/ITS-G5A as the underlying communication technology. The advantages of I2V applications - as indicated in the introduction chapter 1 - are promising which can be a serious motivation to continue the work on this kind of applications and its underlying communication technology. In line with this research, this section provides some notes on future work in the field of I2V traffic efficiency applications.

First, during this research we focused on the I2V communication and assumed several application requirements. Research on better application requirements such as the optimal ZOI could result in more realistic requirements, thus more concrete statements can be made about the underlying wireless communication network.
Second, for all experiments - in addition to the CTLA application - every vehicle was equipped with a beacon service that was broadcasting the CAMs at a frequency of 1 Hz. As stated in the background chapter 2 it is likely that vehicles in a common ITS scenario have deployed many applications, which can result a different channel load. Furthermore, some applications require a much higher beacon rate that 1 Hz, which decreases the load on the channel. Research on the influence of other channel loads can be an interesting further topic.
Third, besides the channel load, the use of different channels has not been tested. For all of our experiments, we assumed all communication to take place at the common channel.
Last, although several researchers started to perform field tests using IEEE 802.11p, at time of writing, there does not exists a completely validated propagation model. During the experiments of this research, we have been varying the transmission power (thus the transmission range) in order to simulate scenarios with varying transmission ranges caused by (mobile) obstacles. In order to make better judgement of VANET performance using a IEEE 802.11p propagation model, validated by field studies, is required.

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